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QUATERNARY ANDESITIC VOLCANISM AT THE SOLANDER ISLANDS

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(Received for publication, 23 June 1958)

Summary

A landing, followed by observations from a fishing launch, has shown that the Solander Islands are erosional remnants of a major volcano consisting of dacitic hornblende-biotite-andesite in the form of lava, tuff, agglomerate, and dykes. Indirect evidence suggests that the rocks are about Upper Pleistocene in age, but more direct evidence might be obtained if ash-showers are found in the sediments of Foveaux Strait and of Stewart Island and the South Island, New Zealand. The volcanism is curiously isolated, the nearest comparable rocks of Tertiary or Quaternary being at Mt. Egmont, 640 miles to the north-north-east. This isolation is a problem of Quaternary tectonics.

INTRODUCTION

The Solander Islands stand like sentinels in the western approaches to Foveaux Strait (Fig. 1), and readers of Bullen's *Cruise of the Cachalot* will recall his vivid descriptions of the continual storms in their vicinity. Bad weather and rough seas have in fact several times defeated the efforts of scientists to land on the islands until Dr R. A. Falla, a biologist, made a landing on Solander Island in 1947, and a landing on Little Solander Island in 1948.

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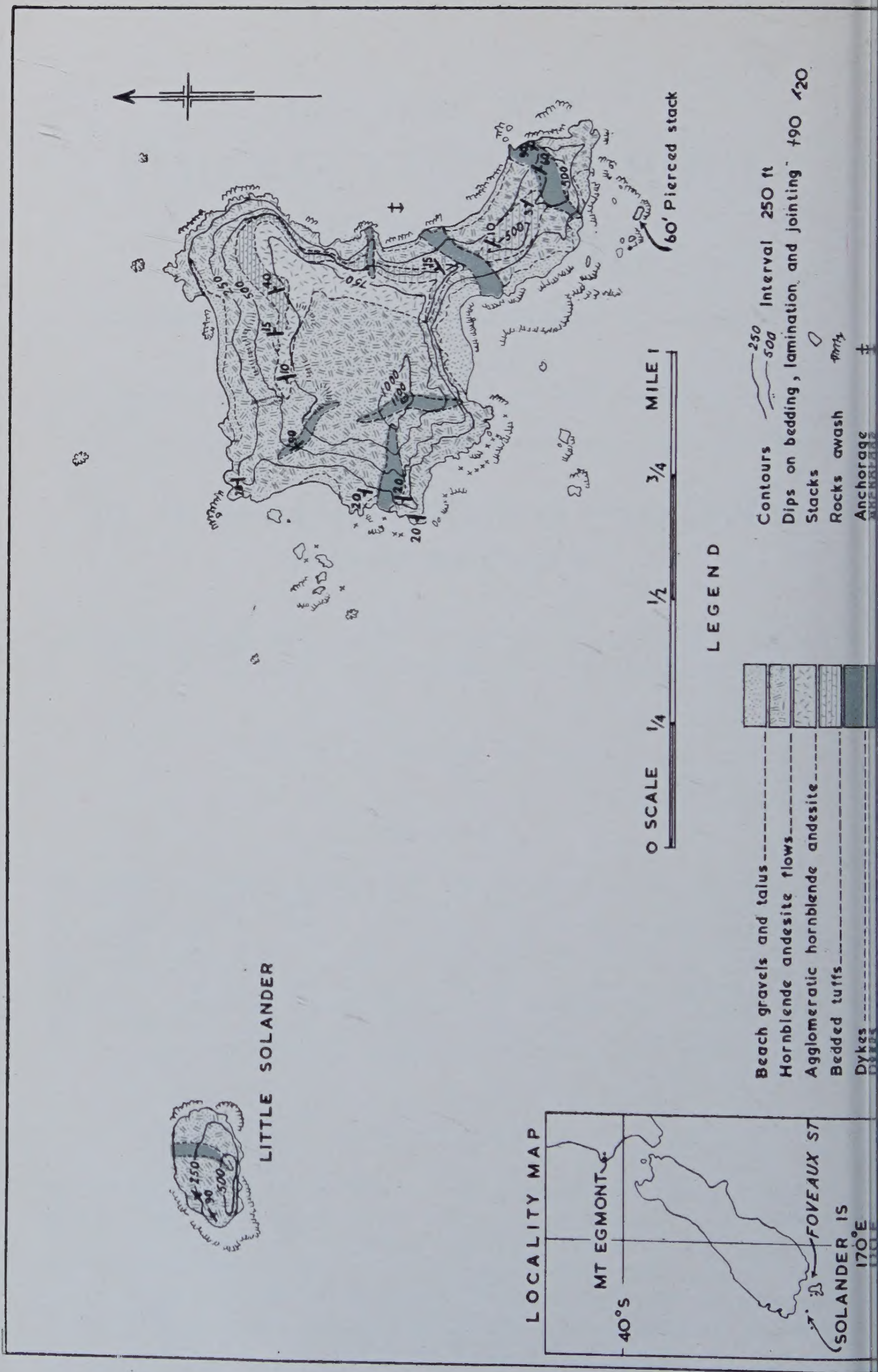

FIG. 1.—Geological and locality maps of Solander Islands.

It could be expected that the Solander Islands would consist of hard pre-Cretaceous igneous, metamorphic or sedimentary rocks like those of the other islands in Foveaux Strait and Stewart Island (Williams, 1934) and parts of the south coast of the South Island. It was with surprise, therefore, that Speight (1909) found that two specimens of hornblende-andesite "as fresh in appearance as many Ruapehu andesites" had been collected by the Captain of the G.S.S. *Hinemoa*. Speight considered that because of their freshness the rocks were likely to be of fairly recent date, "most probably late Tertiaray". The possibility that the specimens were taken from pieces of ship's ballast on the shore disappeared when Dr R. A. Falla landed from the M.V. *Alert* on the "north-east coast" (Falla, 1948) and collected another three specimens from outcrops between the shore and a ridge-crest at a height of 600 ft. Reed (1951) compared these rocks with hornblende-andesites of the New Plymouth district, and like Speight, considered that their unaltered character suggested a Late Tertiary or comparatively recent age. Nevertheless, because the rocks collected by Dr Falla are rather weathered, which obscures their "freshness" in hand specimens, some geologists have been reluctant to accept the suggestion that they are of comparatively young age, and in discussions have suggested other possibilities, for instance, that the Solander Islands lavas might be interbedded with Paleozoic or lower Mesozoic sediments. The Solander Islands are not shown for example, on the map of Late Tertiary and Early Quaternary volcanics by Wellman (1956). Another reason for scepticism about the comparatively young age of the rocks has been that volcanism of andesitic type at the Solander Islands would be curiously isolated by some hundreds of miles from the nearest volcanic activity of comparable age and petrography.

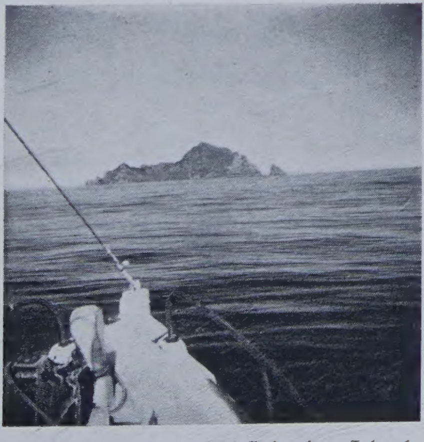

FIG. 2.—Solander Island and Little Solander Island from the east.

In January 1957, at the request of the writers, R.N.Z.A.F. *Tui,* en route to Milford Sound from Bluff, was diverted to Solander Island by Mr J. Brodie and Dr H. Pantin, New Zealand Oceanographic Institute. The weather was too rough to approach closer than half a mile from shore but the main island appeared to be volcanic, and Dr Pantin supplied sketches of a prominent unconformity and other features in the north-western cliffs. (The unconformity is now known to occur within agglomerates.) An echo-sounding traverse was run across the shelf in the vicinity of the islands during that visit, and the submarine topography of the region is desribed below in an Appendix by Mr Brodie.

Through the courtesy of Mr Athol Waddick* the writers were taken to the Solander Islands in the fishing boat *Gekeita* and were landed for an hour on the boulder-beach on the east side of the main island (Fig. 2) on 16 February 1957. A small part of the coast was examined hurriedly for short distances beyond the ends of the beach, and later in the day other parts of the main island were observed and photographed (Figs 3 and 4) from the *Gekeita* at distances of up to a mile or more from shore, before a course was set for Preservation Inlet so as to pass about a mile to the north-east of Little Solander Island.

TOPOGRAPHY

The topography shown on Fig. 3 has been compiled mainly from photographs. The coastline was traced from vertical aerial photographs P.1 to P.4 of Flight 581 of New Zealand Aerial Mapping Ltd., and the form-lines were drawn with the help of horizontal photographs taken from the *Gekeita.*

GEOLOGY OF SOLANDER ISLAND

As soon as the *Gekeita* dropped anchor a few hundred yards from shore it was clear that the island is volcanic, the most striking part of the view being cliffs of light-coloured columnar rock (Fig. 5) resembling in general appearance the cliffs of columnar ignimbrite in the gorges of the Waikato River in the middle of the North Island of New Zealand. Closer inspection on shore showed that the most prominent columnar rocks are generally broad dykes intruded into flows both massive and columnar overlain by bedded tuffs and by

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*Mr A. J. Waddick shortly afterwards lost his life when the *Gekeita* was wrecked at the entrance to Preservation Inlet in April 1957. He was a well-known and resourceful Geological Survey technician from 1948 to 1955 and during that time worked mainly in South Island coalfields, on Tertiary mapping in the rugged country west of the Waiau River in Southland, and in Fiordland. He retained his interest in geology after leaving the Survey to take up crayfishing, and provided transport for expeditions to rarely-visited coastal districts. In February and March 1957, his co-operation enabled a survey to be made by the writers of Solander Island and of the shores of several sounds in Fiordland.

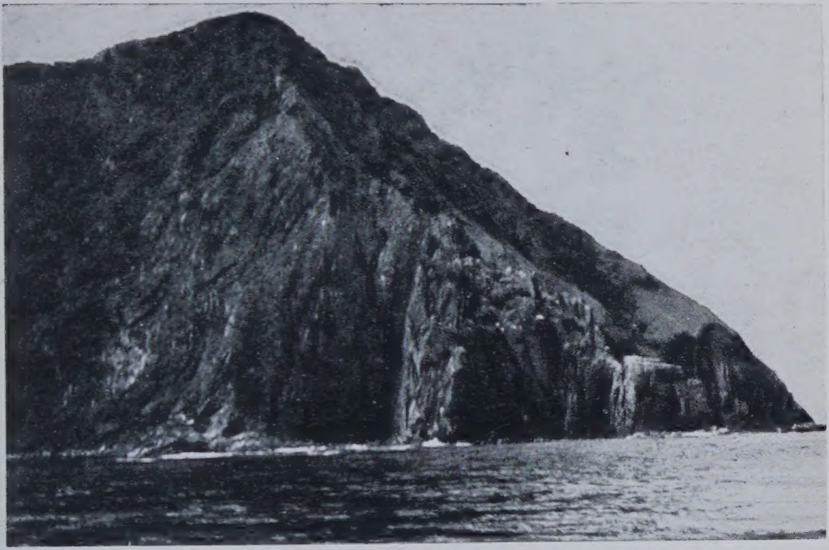

FIG. 3.—South-east end of Solander Island from the south-west.

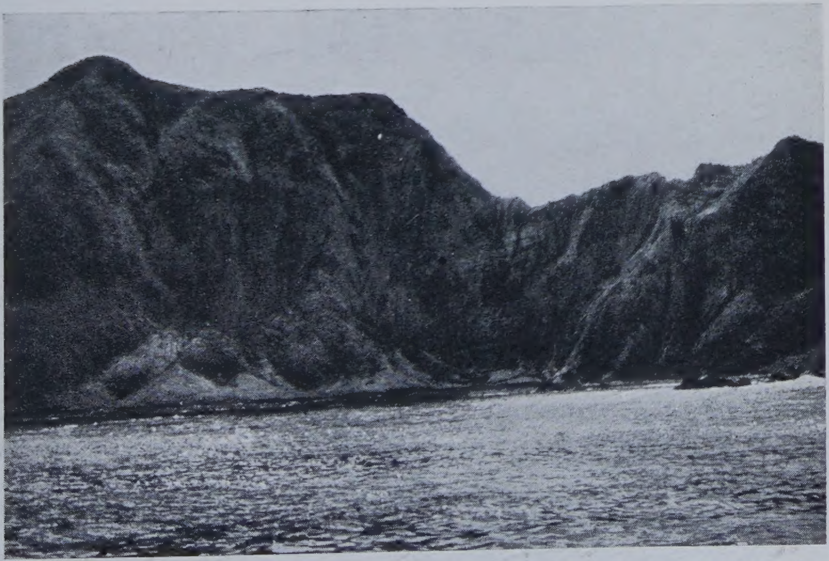

FIG. 4.—South-west bay, Solander Island. In the bluff at the head of the bay bedded tuffs are cut by a broad andesite dyke (right) and dip beneath agglomerate (left).

agglomeratic rocks. Details of cliffs later viewed from the sea were in many places hidden by their bush covering, so that "andesite flows" are shown on the map in places where there are possibly dykes, or even tuffs and agglomerates.

Flows

The greater part of the island, and particularly its lower half, consists of hornblende-andesite flows, some of which are at least 50 ft thick. Outcrops of flows are occasionally featureless except for joints and xenoliths, but usually show sharp joints sub-parallel to the base of the flow passing upwards to thin twisted columns. On the shore, near the anchorage in the east bay, several large beach boulders with a pronounced "laminar-flow structure" were found (Fig. 6). They were at first thought to be bedded crystal tuffs, but are lava flows or dykes consisting of light-coloured out-jutting layers a few inches thick and rich in large plagioclase crystals up to half an inch long alternating with darker thinner layers, rich in large hornblende crystals. Laminar flow structure of a similar kind, though not so pronounced, has been observed by one of the writers (H.J.H.) in boulders contained in lahar deposits at the base of Mt. Egmont.

Tuffs

Bedded tuffs in layers a few inches to a few feet thick, crop out prominently in the lower part of the upper half of the cliffs in the eastern bay above the anchorage, and in the upper parts of the cliffs in the south-west bay. They are roughly 150 ft thick. Fallen blocks of tuff below the cliffs in the eastern bay consist of angular andesite lapillae up to half an inch in diameter, and some blocks have been altered to soft clays probably by fumarolic action. Dips of 0° to 40° in the tuffs (Fig. 4) are considered to be a result, not of folding, but of sub-aerial deposition of ash-showers on the irregular slopes of a volcano.

Agglomerates

Coarse agglomeratic rock, that is possibly for the greater part a true agglomerate formed by explosive activity rather than a lahar, rests on the tuffs in the upper part of the cliffs in the east bay. Its maximum thickness in the cliffs is about 250 ft or more, but the full thickness may be as much as 600 ft if the forested slopes between the cliff-top and the summit of the island are underlain by agglomerate. In the cliffs at the northern end of the island, agglomerate with an apparent dip eastwards of 15° to 40° is overlain unconformably by agglomerate with an apparent dip westwards of 10°. Similar unconformities are common in andesitic volcanoes—as, for example,

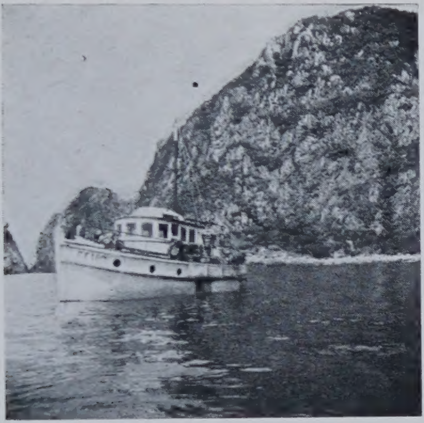

FIG. 5.—Side of a columnar dyke at the south end of east bay.

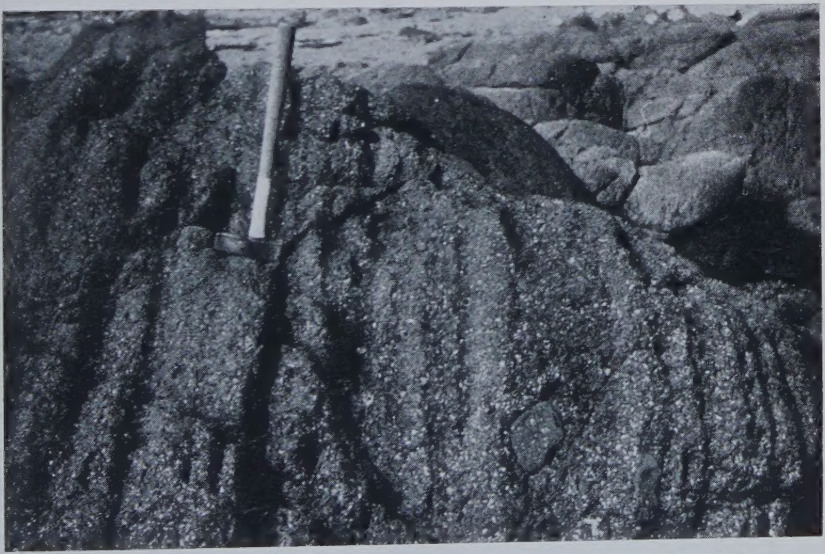

FIG. 6.—Boulder of lava or dyke with laminar flow structure and xenoliths, on the shore of the east bay.

Mt. Tongariro. Three common ways in which they form are by overlapping of the products of adjacent vents, by erosion between periods of eruption, and by caldera collapse followed by renewed eruptions, and one of those mechanisms might explain the unconformity in Solander Island.

Dykes

Figure 5 is a side-view of the great dyke, forming the point at the south-east end of the eastern bay. It consists of large columns rising for over 500 ft above the shore, and cuts through both the flows and the overlying tuffs. Another similar columnar dyke (Fig. 4) extends from the eastern bay to the south-western bay. These dykes are lithologically indistinguishable from the enclosing lavas which are also columnar in places (Fig. 7). Consequently, dykes could be recognized only where they are ridge-formers, and some might have been overlooked.

Petrography

VOLCANIC ROCKS

Speight (1909) described two specimens of hornblende-andesite from Solander Island, and Reed (1951) has described another three typical specimens in greater detail, his account being accompanied by a chemical analysis by F. T. Seelye which shows that the analysed rock has dacitic affinities. Reed also pointed out the strong similarity between the Solander rocks and those described by Hutton (1944) from the New Plymouth area.

The most striking features of all the Solander volcanic rocks in the field and in hand specimens are their light-grey colour and porphyritic nature. The abundant insets of plagioclase (Fig. 8) are commonly half an inch long, and in some rocks are fragments broken from larger crystals during eruption of the lava. They are strongly zoned, and commonly contain many inclusions especially in their outer portions. Hornblende insets are smaller and less abundant. In one rock they are greenish-brown in colour, but are normally oxyhornblende pleochroic from light-yellow-brown to deep brown. Bent biotite flakes are also usually present among the insets in small amount and are pleochroic from medium brown to very dark brown. Small crystals of iron-titanium oxide are scattered through all slides, and the texture is usually hyalopilitic. Apatite in large needles and zircon are present as accessories.

XENOLITHS

Angular and sub-angular xenoliths usually 2 to 3 inches in diameter are abundant in some flows and dykes, and have sharp edges without signs of resorption. Those sampled are all andesite, or hornblende-diorite crystallized at depth from the same magmas that were erupted as lavas. A short unsuccessful search was made for xenoliths of Tertiary sediments and of Lower Paleozoic rocks.

A flow towards the north end of the eastern bay contains lumps of pumiceous dacitic andesite resembling the fluffy pumice lumps found in the upper parts of ignimbrite sheets in the central North Island region.

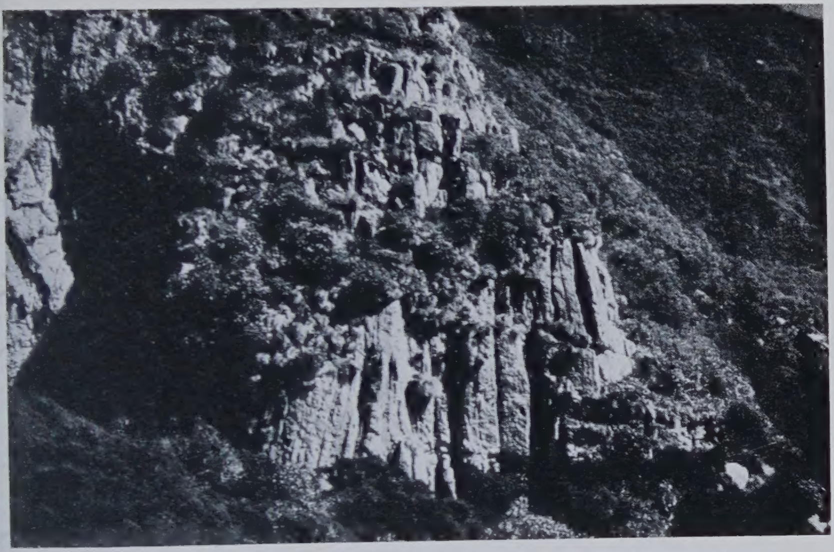

FIG. 7.—Columnar lava towards the south end of the east bay.

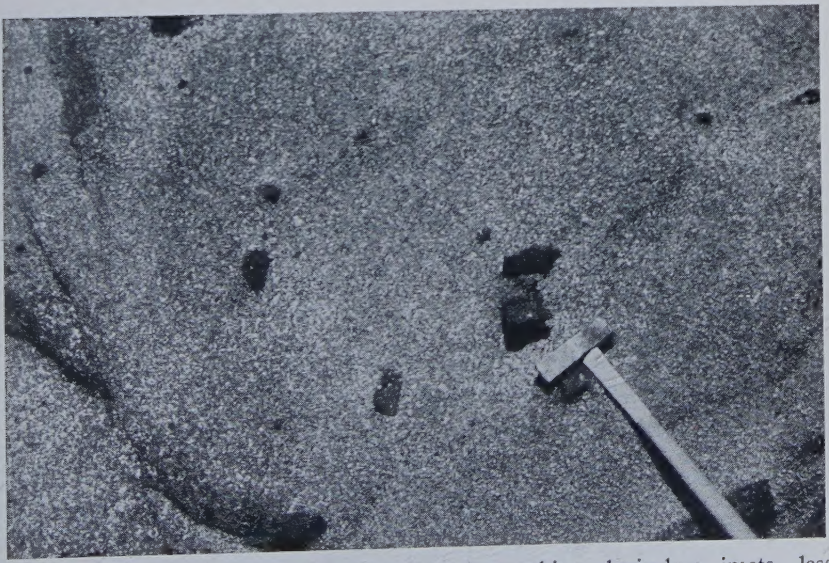

FIG. 8.—Typical andesite lava with abundant white plagioclase insets, less abundant hornblende insets and scattered xenoliths of hornblends-diorite.

The diorite xenoliths consist of plagioclase, brown hornblende, a little dark brown biotite and, in one rock, interstitial quartz, and hence differ very little from the andesites except in degree of crystallization and absence of primary iron-titanium oxides.

Age of Volcanism

There is at present no direct evidence of the age of the volcanic rocks of the Solander Islands. The "fresh" or uncompacted character of the rocks is reliable indirect evidence (in a New Zealand environment) that they are not of Mesozoic age or older. Consideration of the general history of volcanism in New Zealand makes it tolerably certain that such fresh rocks are no older than Altonian (Lower Miocene) and probable that they are no older than Taranakian (Upper Miocene). The islands are now merely dissected remnants of part of a central volcanic complex or of the rim of a caldera, and though marine erosion must be very rapid in this storm-swept region it is likely, considering the large amount of erosion that seems to have occurred, that the rocks at present exposed on the islands are no younger than the Last Glaciation of the Pleistocene. Similarly, any part of a Pliocene or Lower Pleistocene volcano that rose above the sea would almost certainly have been removed by marine erosion, so that the rocks at present exposed are possibly of about Upper Pleistocene age. Beneath the sea there might be other rocks that are the products of intermittent eruptions in both Pliocene and Pleistocene time.

It may be commented that the volcanism at Mt. Egmont and associated centres in Western Taranaki is comparable in regional setting and petrology with that of the Solander Islands, and is probably entirely of Upper Pleistocene age (Fleming, 1953; Hutton, 1944).

Several different kinds of evidence could provide a closer estimtae of age. Plant remains or other fossils might yet be found in the tuffs of Solander Island. The existence of tuffs suggests that the dust of ash-showers could have been carried by the strong prevailing winds to the southern part of the South Island and Stewart Island, and might be found there in soils* or Quaternary sediments. Lastly, material was collected which it is hoped can be dated by the ^{40}K — ^{40}A isotope method.

Ash-shower material and crops of volcanic hornblende and plagioclase crystals might be found in the sediments of Foveaux Strait.

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*A soil reconnaissance of south-western Southland by Wright (1951) showed that many of the soils on the undulating landscape bordering Foveaux Strait were derived from "loess-like" material. This material appears to be much richer in iron than the regional loess of Southland, and closely resembles volcanic ash. It is found also on the summit of the Longwood Range, in the south-western part of the Catlins Ranges and on Stewart Island (Mr A. C. S. Wright, pers. comm.). It should be possible to estimate the age of this material by reference to Quaternary coastal terraces.

HISTORY OF VOLCANISM

Only a fragment of the full history of volcanism at the Solander Islands can be reconstructed. Eruption of flows was followed by the deposition of ash-showers, which in turn were covered, at least locally, by agglomerates. The intrusion of dykes up to 100 yards wide occurred after deposition of the tuffs, and possibly during or after the formation of the agglomerates.

The distribution of the tuffs and the dips recorded in them vaguely suggest that Solander Island is part of the north-eastern side of a former cone, or alternatively the north-eastern part of the exterior slope of a caldera rim and, therefore, that the vent or vents from which the tuffs were erupted lay to the west or south-west of Solander Island. In any case, by analogy with most other andesitic eruptive centres, volcanism was probably fairly long-lived, and might have passed through phases of both cone-building and caldera formation. The present islands could be either a portion of a former large composite volcano, or the remnant of a cone thousands of feet high not unlike Mt. Egmont.

Further evidence concerning the submarine distribution of the volcanic rocks might be obtained by surveys of the sea-floor and of gravity and magnetic anomalies.

ISOLATION AND CAUSE OF VOLCANISM

The nearest volcanics of Tertiary or Quaternary age similar to the andesites of the Solander Islands occur at Mt. Egmont and New Plymouth, 640 miles to the north-north-east (Fig. 1). This curious isolation and the cause of the volcanism are aspects of Quaternary tectonics, a problem which is being actively investigated by several New Zealand geologists and geophysicists. The solution to the problem is only partly understood, but knowledge of the relationship of Tertiary and Quaternary volcanism in New Zealand (including the Solander Islands) to patterns of seismic activity, gravity anomalies, transcurrent and other faulting, and of the present direction of principal horizontal stress in the crust has been summarized on maps by Grindley and Harrington (in press).

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APPENDIX

THE SEA-FLOOR AROUND THE SOLANDER ISLANDS

By J. W. BRODIE, New Zealand Oceanographic Institute, Department of Scientific and Industrial Research

The Solander Islands rise from the outer edge of the continental shelf. Depths nearby range from 70 to 100 fathoms and the sea-floor in the immediate vicinity of the islands is irregular.

South of the group, beyond the shelf-edge, there is a large linear depression (Fig. 9) which has been named the Solander Trough

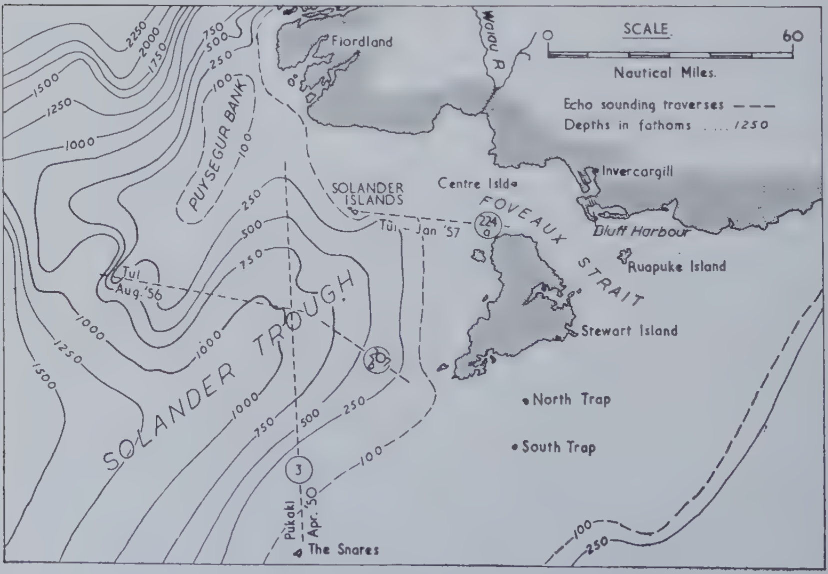

FIG. 9.—Sea-floor topography in the vicinity of the Solander Islands.

(Brodie, 1958). This feature, which has been defined by echo-sounding traverses from R.N.Z.F.A. *Tui* and H.M.N.Z.S. *Pukaki*, has an axis trending roughly north-east to south-west and a length of about 80 miles. It is about 20 miles wide at the 1,000 fathom isobath, and 50 miles across at the 250 fathom isobath. In cross-section the trough is slightly asymmetric, the western slopes being the steeper. The trough bifurcates in its north-eastern part, one branch passing west of the Solanders towards the channel between Puysegur Bank and the mainland, the other passing just east of Solander Island towards the Waiau depression. There is no trace of an extension of the eastern branch furrowing the shelf. The Solander Islands lie generally just west of the projection of the axis of the main trough.

There are insufficient soundings to consider in detail the geological implications of the bathymetry, but the alignment of the eastern branch of the trough with the Waiau syncline (see Brodie, 1958) and the association of the Solander volcanics with the trough axis, can hardly be fortuitous.

It is not unreasonable to suppose that the trough has existed as a tectonic depression at least as early as major movements in the analogous Waiau syncline, that is, since Miocene time.

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URANIUM MINERALIZATION IN THE HAWKS CRAG BRECCIA OF THE LOWER BULLER GORGE REGION, SOUTH ISLAND, NEW ZEALAND

By A. C. Beck, J. J. Reed, and R. W. Willett, New Zealand Geological Survey, Department of Scientific and Industrial Research

(Received for publication, 20 June 1958)

Summary

Bedded uraniferous deposits have been discovered in the middle (?) Cretaceous Hawks Crag Breccia formation of the lower Buller Gorge region of the South Island of New Zealand, and in three areas to the south (Bullock Creek, Waitahu River, and Fox River mouth). The characteristic feature in all the areas is the restriction of the mineralization to the arkosic facies of the Hawks Crag Breccia.

On the north side of the Buller Gorge, at least ten uraniferous horizons are known, ranging in width from a few inches to several feet. Within each horizon the mineralization is patchy. The main primary uranium mineral is coffinite which has been introduced along with pyrite, carbonate (largely ferroan dolomite), and red hematite staining of the clastic feldspar. Secondary uranium minerals are generally inconspicuous. The deposits are considered to result from low-temperature mineralization by epigenetic solutions, but it is still uncertain whether the uranium originated from dispersed sources in the arkosic sediments or was introduced in hypogene solutions from lamprophyres and porphyries.

Minor uranium concentrations are associated with a poryphyry dyke in Hawks Crag Breccia, and with quartz veinlets and lodes in granite-gneiss and Greenland sediments.

A comparison is made between mineralization in the Buller Gorge and on the Colorado Plateau.

Introduction and History

The main uranium deposits described in this paper are located in the lower Buller Gorge region of the South Island of New Zealand, about 15 miles east of the rail and shipping centre of Westport (Fig. 1). The country is heavily bushed and mountainous and has a high rainfall. Other, less prospected, deposits have been discovered in Bullock Creek, Waitahu River, and Fox River mouth, to the south of the Buller Gorge (Fig. 1).

The search for radioactive minerals in New Zealand has been carried out somewhat irregularly. During the second World War, examinations

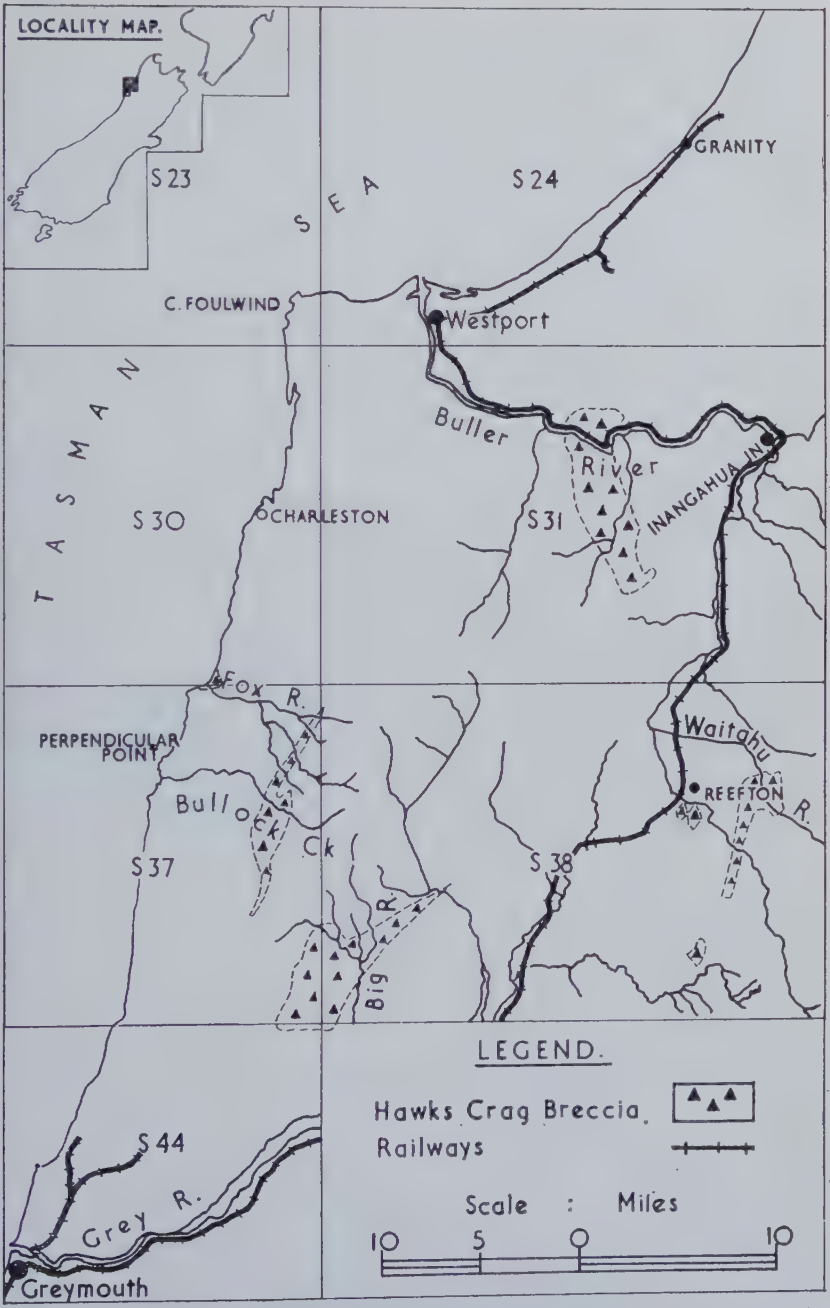

FIG. 1.—Map showing distribution of Hawks Crag Breccia on west coast of South Island of New Zealand.

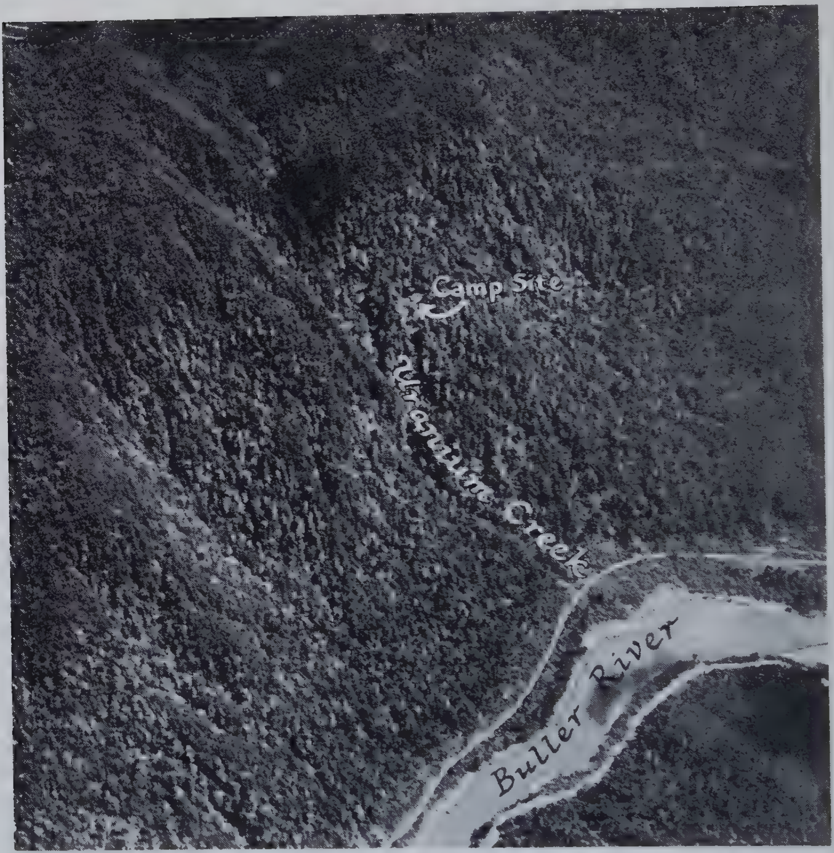

FIG. 2.—Aerial photograph of lower Buller Gorge showing mountainous nature and heavy bush cover. Photograph looking north along Uranium Creek draining Trig C. Buller River in right foreground, with railway on north side, and main road on south. Radioactive horizons run in a north-easterly direction above and below camp site.

—*Photo*: *S. N. Beatus*

were made of the blacksand areas of the West Coast and of the granites and gneisses of Fiordland, Westland, and Nelson. The work disclosed that the black sands of the west coast of the South Island did carry some radioactive minerals, mainly uranothorite (Hutton, 1950). Some consideration was given to the question of saving the heavy minerals from the tables of the alluvial dredges then operating, but for various reasons the plan was not developed (Nicholson, 1955). As the outcome of these activities was discouraging, interest in a probable occurrence of radioactive minerals in New Zealand diminished. It was generally held that there were insufficient radioactive minerals in the blacksand to warrant winning, and that the granites and associated rocks of New

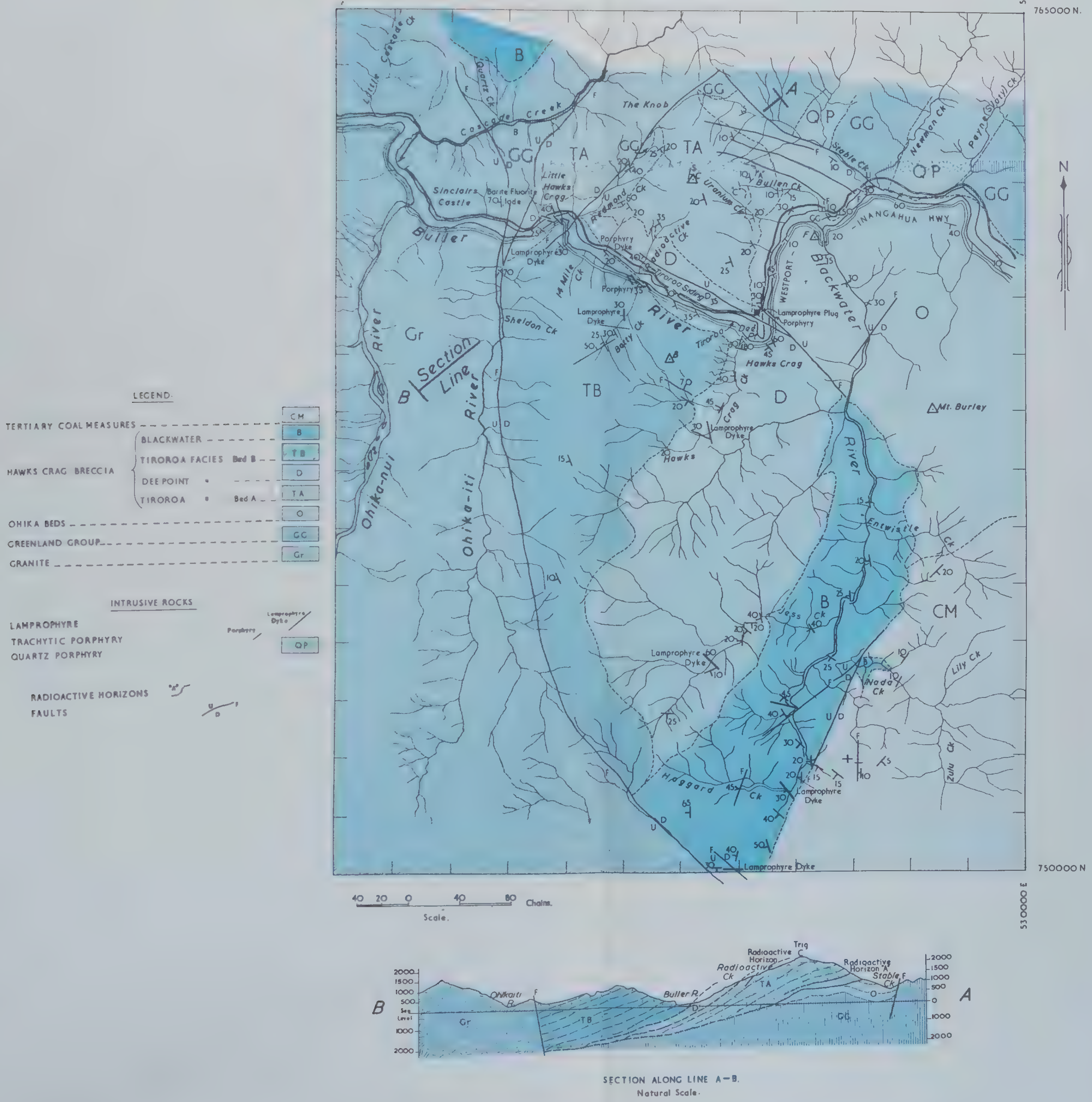

Fig. 3.—Detailed geological map of lower Buller Gorge.

Zealand held little promise. This view was supported by visiting overseas authorities. It tended to deaden the search, and it was not until after visiting Australia that the then Director of the Geological Survey, Dr L. I. Grange, sought to forward the search in New Zealand. The appearance of a handbook, "Prospecting for Radioactive Minerals in New Zealand", by Grange (1954), helped to stimulate the search, and as a result many samples were examined by the Geological Survey. Although the samples received from prospectors by the Survey covered the length and breadth of New Zealand, results were again negative. This phase of the search tended to concentrate on the granites and the metamorphic rocks and some of the older sandstones and conglomerates. In November 1955, Mr C. E. Jacobsen arrived at the Geological Survey with a bag of samples which proved to be far more radioactive than anything that had previously been examined. These samples were without doubt the first promising strongly radioactive New Zealand rock that the Survey had examined. Although at that time ignorant of the locality of the samples, Geological Survey petrologists were able to place the rock in the Hawks Crag Breccia, a deduction which was later confirmed by the announcement by the discoverers of their locality. These samples were from the "hottest" spots on the outcrop, and later examination revealed that the rest of the outcrop was very low in activity. In the search for radioactive minerals, this find by Messrs Jacobsen and Cassin was of great geological significance, for overnight it transferred geological thinking from the granites and associated rocks to a hitherto unsuspected arkosic bedded rock known as the Hawks Crag Breccia. The geology of the Hawks Crag Breccia and its distribution throughout north Westland was already fairly well known, and maps showing this distribution had already been published (Wellman, 1950). Subsequent prospecting activity in the Buller district resulted in various claims being pegged out in the adjacent areas. Interest at this stage was largely confined to the Hawks Crag Breccia within the Buller Gorge, but the other Hawks Crag Breccia areas soon began to receive attention from prospectors. Both in the initial press reports and in the revised edition of the handbook (Grange, 1956), the find by Messrs Jacobsen and Cassin was described as a lode. Further prospecting work in other parts of the Buller Gorge, and geological examination proved this not to be the case. Finally, it has been demonstrated that the radioactivity is confined to a particular facies of the Hawks Crag Breccia. This is the substance of the present paper. The find of Messrs Jacobsen and Cassin is now explained by deposition of radioactive minerals along an intrusion of porphyry. Up to the present time, the greater amount of prospecting has been done on the northern side of the Buller Gorge, over a large area originally held by Lime and Marble Ltd., now held by Buller Uranium Ltd. The information revealed by prospecting has provided the main geological data for this paper. The hypothesis that the radioactivity is confined to one particular facies was established in this area and has been demonstrated to be sound in other Hawks Crag areas in the north Westland district.

TABLE 1.—Stratigraphic Sequence in Lower Buller Gorge.

	Lithology	Age
Tertiary	Non-marine at base	Eocene-Pliocene
	UNCONFORMITY	
Porphyry	Soda trachyte	Upper Cretaceous(?)
Lamprophyre	Camptonite, vogesite monchiquite	upper Cretaceous(?)
Hawks Crag Breccia	Conglomerate, breccia, sandstone, siltstone	Middle(?) Cretaceous
	UNCONFORMITY	
Ohika	Shales, conglomerates, vitric tuffs	Jurassic
	UNCONFORMITY	
Quartz porphyry	Quartz porphyry, granite porphyry	Jurassic(?)
Granite	Granite gneiss, diorite gneiss, pegmatite, hornfels, schist	Lower Paleozoic and/or Pre-Cambrian(?)
Greenland	Greywacke, phyllite, schist	Lower Paleozoic or Pre-Cambrian(?)

GENERAL GEOLOGY

The stratigraphic sequence of rocks in the lower Buller Gorge is shown in Table 1 and their areal extent in Fig. 3.

The oldest rocks are a basement of Greenland sediments, and granite. The Greenland rocks are unfossiliferous quartzo-feldspathic hornfelsic greywackes, phyllites, and schists, generally much sheared and shattered, and with inconspicuous bedding. Where discernible, the bedding conforms to the regional north-west strike of the Greenland Group (Wellman, 1956: 23). The age of the sediments is either lower Paleozoic or preCambrian. The granitic rocks of this area have been mapped under the broad term "granite" (Morgan and Bartrum, 1915), but, in general, they are gneissic, and range in composition from granitic to dioritic, enclosing xenolithic bands and remnants of biotite, schist, and hornfels. The granitic rocks are here faulted against the Greenland Group, but outside the lower Buller Gorge area, bosses intrusive into Greenland are known. It is not certain whether the Buller Gorge granitic rocks are younger or older than the Greenland sediments.

Quartz porphyry, intrusive into Greenland sediments, is known from several localities (Fig. 3). In general, it is coarsely crystalline and contains a few xenoliths, but near Berlins greywacke xenoliths are abundant, and, on weathered surfaces, give the rocks the appearance of a breccia. The quartz porphyry is unconformably overlain near Berlins by the Mesozoic Ohika beds (Wellman, 1950), but the fact that the Ohika beds contain plentiful acidic vitric tuffs indicate that acid volcanic activity was continuing not far away, so that there is probably no great time interval between the two formations. It is probable that the quartz porphyry was a tuffisite feeder dyke for the outpouring of vitric tuff.

The Ohika beds rest unconformably on both the Greenland Group and quartz porphyry. Near Berlins, the lowest beds consist of a conglomerate up to 100 ft thick containing greywacke and quartz porphyry fragments. Above this is up to 500 ft of dark fissile shale and carbonaceous mudstone which afford a very good mapping horizon. Near the Blackwater Bridge, the fissile shales are overlain by 150 ft of acidic vitric tuffs containing carbonaceous specks. Above the tuffs are coarse quartzose sandstones and conglomerates up to 500 ft thick. A noteworthy feature of the conglomerates is the presence within them of fragments, commonly angular, of the underlying carbonaceous mudstone and fissile shale; this indicates considerable tectonic activity during the period in which the Ohika beds were laid down. Both the rank and determinable thickness of the sediments increase to the west. A Jurassic age is indicated by spore determinations (Couper, *in* Wellman, 1950).

The unfossiliferous Hawks Crag Breccia containing the bedded uraniferous deposits is described below in detail. The contact with Ohika was considered a transitional one by Wellman (1950), but recent mapping has revealed an unconformity. The age is probably middle Cretaceous.

Lamprophyric dykes and sills cut Hawks Crag Breccia, Ohika beds, and granite (Fig. 3). The average width is 3 ft, although some are up to 10 ft. At Dee Point, a roughly circular intrusion is considered to be a volcanic pipe. The rocks are camptonites, vogesites, and monchiquites, generally fine grained, and containing abundant secondary carbonate (mainly ferroan dolomite), and less plentiful pyrite and quartz and rarely barite. Xenoliths of country rock are not uncommon. The lamprophyres are probably pre-upper Cretaceous in age, as lamprophyric pebbles have been reported in upper Cretaceous (?) coal measures of the Greymouth region (Gage, 1952; 26).

Porphyry dykes cutting Hawks Crag Breccia are known only in a restricted part of the region (Fig. 3). All are intensely altered sodic types in which the trachytic texture is still preserved. The majority

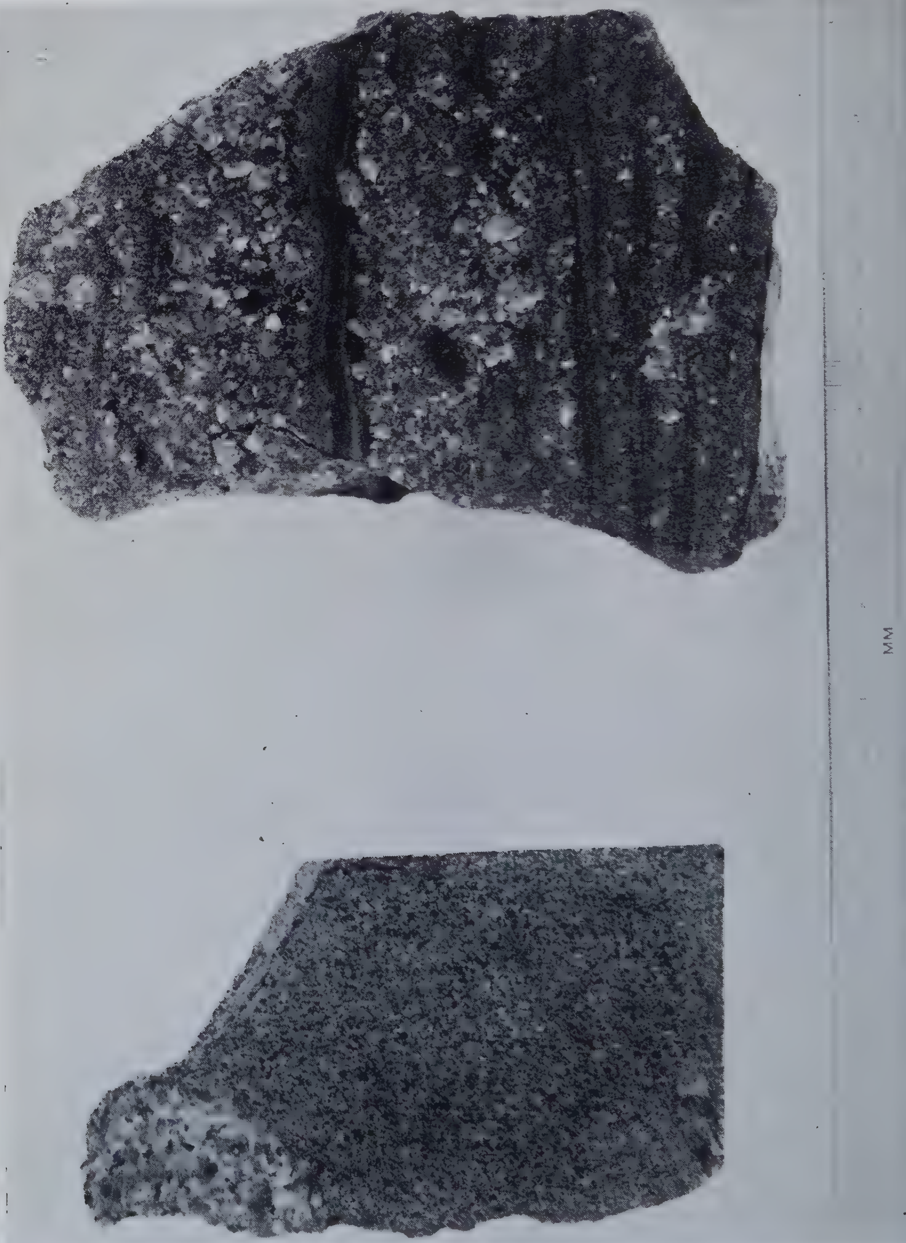

FIG. 4.—Photograph showing structure and degrees of sorting in typical radioactive rocks of Tiroroa facies, Hawks Crag Breccia.
Upper: arkosic breccia, grit, and siltstone.
Lower: arkosic grit with granite pebble.

—*Photos*: *S. N. Bea*

are chalk-coloured sericitized rocks, but that near Batty Creek, with which the first uranium discovery is associated, is pinkish in colour. The porphyries are not known outside the lower Buller Gorge area; their age is probably upper Cretaceous.

Resting with angular unconformity on both Ohika and Hawks Crag Breccia are Tertiary sediments ranging in age from Eocene to Pliocene. These have been described by Wellman (1950) and will not be considered further, as no uranium minerals have been found in them.

HAWKS CRAG BRECCIA

The Hawks Crag Breccia forms long belts bounded on at least one side by a major fault and has the appearance of having been laid down in a fault-angle depression. The bedding is relatively simple, the rocks dipping generally south-west at angles of up to 40° into a major fault in Ohika-iti River, which separates the breccia from granite gneiss.

The beds are non-marine coarse angular sandstones, siltstones, conglomerates, and breccias which are composed of mechanically weathered material. The sediments are largely unsorted, many beds containing boulders up to 10 ft in diameter set in a coarse grit matrix (Fig. 4). In general, the large boulders, particularly of granite, are sub-rounded, in contrast to the angular nature of the grit matrix. Bedding is commonly shown by the thin silt and sand bands and is very regular. Plant remains and carbonaceous staining are common in some of the rocks.

The Hawks Crag Breccia can be subdivided into three facies on the composition of the parent material (Table 2). The Tiroroa facies* is characterized by its arkosic nature, the rocks being derived from a

Table 2.—Facies in Hawks Crag Breccia.

Facies	Approximate thickness (ft)	Parent rock	Type area
Tiroroa B	2,500	Granite	South side, Buller River
Dee Point	600	Greenland greywacke	Hawks Crag, Dee Point
Interfingering Zone	5–100	Granite and greywacke	Batty Creek
Tiroroa A	2,500+	Granite	North side, Buller River
Blackwater	—	Granite and greywacke	Blackwater River

*See footnote p. 440.

plutonic terrain in which granite was dominant, but in which gneiss, schist, hornfels, and greywacke occurred. This facies crops out in two areas which are separated stratigraphically by the Dee Point facies. The older beds, designated Tiroroa facies A, rest unconformably on fissile shales of the Ohika Group, on the northern side of the Buller River. The stratigraphically older beds, designated Tiroroa facies B, occupy a larger area extending from Buller River to the headwater of Blackwater River and along the Ohika-iti River. A zone of interfingering with the underlying Dee Point facies, ranging in thickness from a few feet to about 100 ft, is exposed in the Buller River at Batty Creek, and high in the western tributaries of Hawks Crag Creek. The Dee Point facies,* typically developed at Hawks Crag, is a breccia consisting almost entirely of angular unsorted phyllitic greywacke derived from the Greenland Group. It is cemented by a ferruginous matrix, weathering of which has imparted a maroon colour to the rocks. Very few carbonaceous bands are present, and, where they are, the maroon colour is absent. Bedding is less common than in the other facies. The Dee Point facies rests on Tiroroa facies A on the north side of the Buller River, and on Ohika beds between the Buller River and Blackwater River. In the upper Blackwater River they rest on Blackwater facies composed of arkosic and greywacke material set in a fine-grained greywacke matrix. The greatest area of Blackwater facies is exposed in the headwaters of the Blackwater River, where it appears to be in a basal bed, but the sedimentary contact with basement rocks is not exposed.

BEDDED URANIFEROUS DEPOSITS

Bedded uraniferous deposits are confined to the Tiroroa facies and interfingering zone of the Hawks Crag Breccia. The most prospected area is north of the Buller River in Tiroroa facies A, where at least 10 uranium-bearing horizons are known ranging in width from a few inches to several feet. Within a horizon, mineralization is patchy, varying from less than 0·025% to 6·4% U_3O_8. The radioactivity is due to uranium, and no significant amounts of thorium have been detected. The main primary mineral is coffinite, hydroxyl-substituted uranous silicate (Reed and Claridge, 1957), which possesses the same properties as the type material from the Colorado Plateau (Stieff, Stern, and Sherwood, 1956). The most significant feature is the very fine grain size as indicated by its apparent isotropy under the microscope. The coffinite† is deposited interstitially around the clastic grains and pebbles

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*Mr D. Kear, Geological Survey, who has recently visited the Buller Gorge area, interprets the Dee Point facies as a true scree deposit, and the Tiroroa facies as an alluvial conglomerate.

†Williams (1957, p. 15) quotes an age determination of the Rio Tinto Company on a sample of Buller George coffinite as lying within the range of 100,000,000 to 150,000,000 years. This would indicate a Cretaceous age for the mineralization.

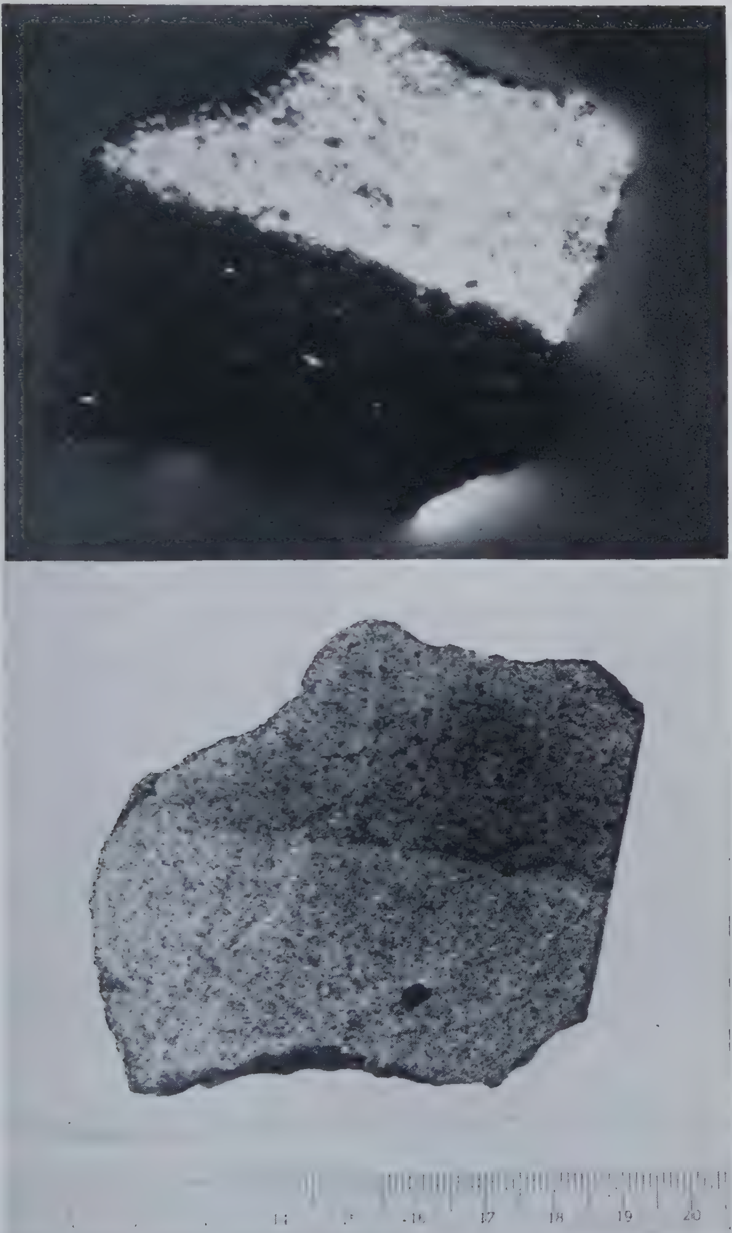

FIG. 5.—Autoradiograph (upper) showing distribution of radioactivity in matrix of arkosic Hawks Crag Breccia sample (lower). Autoradiograph positive with high radioactivity white coloured. The upper portion of the rock assayed 6·5% U_3O_8 and the lighter-coloured portion 0·26% U_3O_8.

—*Photo: S. N. Beatus*

and is intimately admixed with pyrite and carbonate (Fig. 5). The carbonate is in part calcite and in part ferroan dolomite (para-ankerite); the dolomite possesses the same optical preperties ($N_o = 1{\cdot}6985 \pm 0{\cdot}005$; $N_e = 1{\cdot}5150 \pm 0{\cdot}0005$) as the ferroan dolomite associated with the lamprophyres.

It is clear that the coffinite, pyrite, and carbonate are epigenetic in origin. Closely linked with the introduction of these minerals is red hematite staining of the clastic feldspar, particularly of plagioclase. Because of the impregnation with coffinite and hematite, the radioactive horizons are both darker and redder than the non-radioactive layers, although there is no difference in lithology. The chemical differences between the two layers are clearly indicated in Table 3. The great excess of carbon dioxide over the available lime in the analysis of the radioactive horizon will be noted.

Uraniferous hydrocarbon is known to be present in some of the radioactive horizons, but as yet no uraninite has been identified. Secondary uranium minerals are generally inconspicuous, although in places autunite and uranophane are not uncommon. Fluorite is an additional member of the epigenetic assemblage in radioactive rocks from Radioactive and Redmond creeks. The fluorite is characteristically purplish in colour and is deposited interstitially in the matrix, as patches in the carbonate, and as "veins" in mica. Slightly radioactive quartz-fluorite-pyrite veinlets cutting Tiroroa facies A are known in Radioactive Creek.

The Tiroroa facies south of the Buller River has been little prospected, but bedded uranium deposits have been found in a tributary of the Ohika-iti River and as boulders in Hawks Crag Creek.

OTHER URANIUM OCCURRENCES IN LOWER BULLER GORGE

The most interesting of the other uranium occurrences in the lower Buller Gorge is the Batty Creek "lode", the original discovery by Messrs Cassin and Jacobsen. The radioactivity is concentrated at the foot wall of a porphyry dyke in Hawks Crag Breccia, and has been traced for several chains from the roadside outcrop to Batty Creek. The highest value obtained was 0·28% U_3O_8, but the activity is generally much lower and very patchy. The mineralizing solutions have affected both the porphyry dyke and the adjacent arkosic Hawks Crag Breccia, the uranium being concentrated in part, if not entirely, in veins and disseminated aggregates of minute euhedral crystals of zircon (variety cyrtolite). Linked with the radioactivity is hematite coloration and introduction of silica, soda, and molybdenum (Table 3). It may be remarked that the Batty Creek "lode" and the other altered porphyry dykes bear many similarities to the porphyries of the Central City District, Colorado, described by Phair (1952).

In the railway cutting near Sinclair's Castle a radioactive quartz veinlet containing uraniferous hydrocarbon cuts granite-gneiss, on the surface of which secondary meta-autunite is not uncommon. Radio-

TABLE 3.—Chemical Analyses of Radioactive and Non-radioactive Arkosic Sandstones of Tiroroa Facies, Hawks Crag Breccia, and of the radioactive Batty Creek "lode".

	A	B	C
SiO_2	61·4	73·3	60·7
Al_2O_3	11·2	12·8	16·1
Fe_2O_3	1·7	0·5	2·75
FeO	2·25	1·1	0·75
MgO	2·1	0·7	0·3
CaO	5·3	1·1	0·1
Na_2O	2·7	2·8	8·5
K_2O	3·0	3·3	0·6
Li_2O	n.f.	n.f.	n.f.
H_2O+	1·4	1·4	1·2
H_2O-	0·43	0·45	0·27
TiO_2	0·18	0·08	0·31
P_2O_5	0·26	0·10	0·32
MnO	0·15	0·03	0·02
CO_2	6·8	1·1	0·01
S	0·72	0·28	0·18
C	0·04	0·03	0·06
U_3O_8	0·62	—	0·15
MoO_3	0·01	—	0·48
ZrO_2	n.f.	—	6·4
	100·3	99·1	99·2

Molecular Norms

	A	B	C
Q	31·5	41·9	8·2
or	18·0	20·5	3·5
ab	24·5	26·0	79·0
C	3·8	5·2	1·7
en	—	1·2	1·0
fs	—	0·6	0·2
mt	1·8	0·5	0·2
il	0·4	0·2	0·4
hm	—	—	2·0
ap	0·5	0·3	0·3
pr	1·8	0·8	0·5
cc	10·0	2·0	—
$MgCO_3$	6·0	0·8	—
$FeCO_3$	1·3	—	—
coffinite	0·4	—	—
ZrO_2	—	—	3·0
MoO_3	—	—	0·2

A. Radioactive arkosic sandstone, P. 16590, A-horizon, Tiroroa facies A, Hawks Crag Breccia, lower Buller Gorge.
—Analyst, J. A. Ritchie, Dominion Laboratory

B. Non-radioactive arkosic sandstone, P. 16715, immediately below A-horizon, Tiroroa facies A, Hawks Crag Breccia, lower Buller Gorge.
—Analyst, J. A. Ritchie, Dominion Laboratory

C. Batty Creek "lode" (uraniferous porphyry and Hawks Crag Breccia), P. 16312, roadside outcrop, lower Buller Gorge.
—Analyst, J. A. Ritchie, Dominion Laboratory

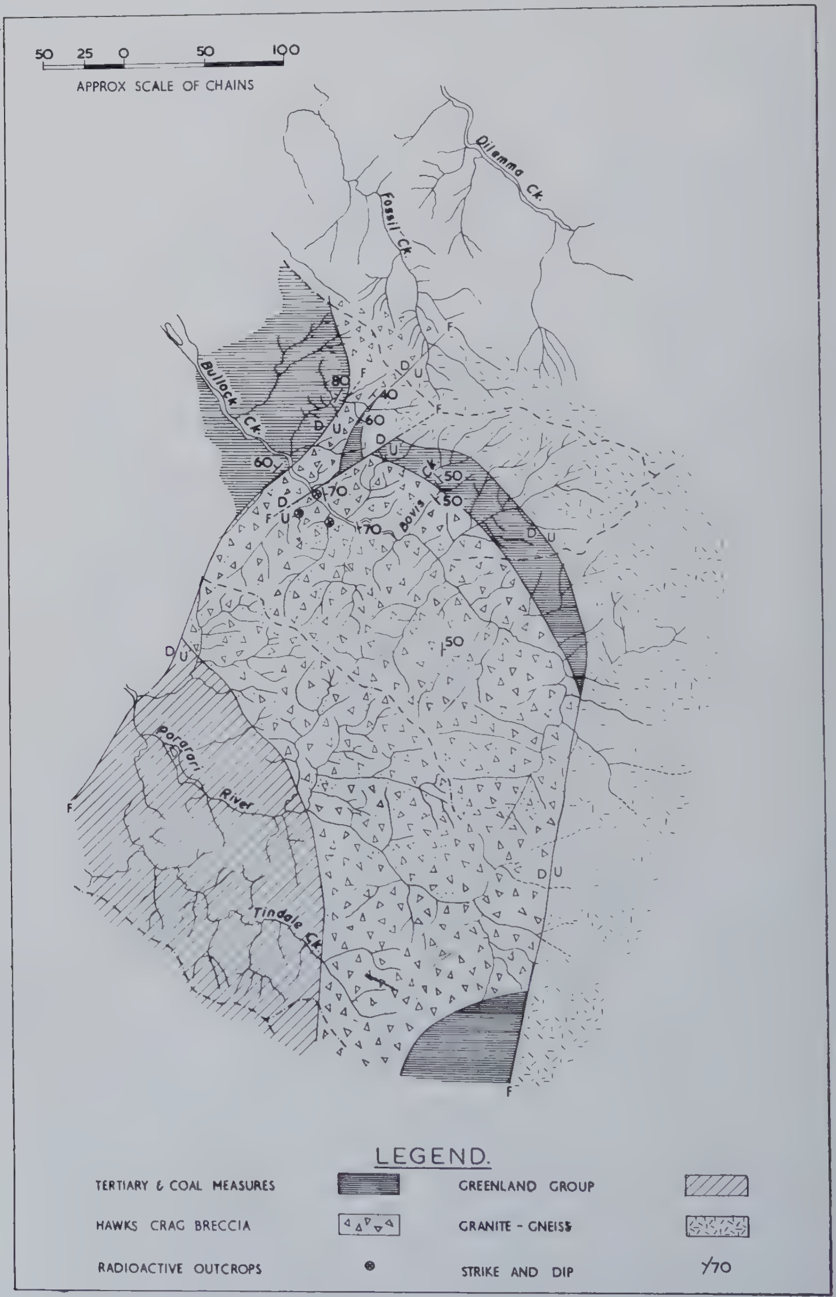

FIG. 6.—Detailed geological map of Bullock Creek area.

activity has also been detected in quartz-pyrite veins in granite-gneiss in Mispickel Creek, near Sinclair's Castle, and in quartz-pyrite-molybdenite lodes in Greenland rocks in Quartz Creek, a tributary of Cascade Creek.

RADIOACTIVITY IN HAWKS CRAG BRECCIA AT BULLOCK CREEK, WAITAHU RIVER, AND FOX RIVER MOUTH

The Hawks Crag Breccia in the Bullock Creek area (Fig. 6) is composed of granitic pebbles and boulders set in an arkosic matrix very similar to the Tiroroa facies in the Buller Gorge, but the induration of the rocks is greater. As in the Buller Gorge, there is a range of lithological types from boulder beds to carbonaceous siltstones, none of which is persistent for any distance laterally. Bedding, where observed, dips uniformly at high angles (60° to 85°) to the east, the general strike being 350°. The uraniferous deposits so far discovered closely resemble those in the Buller Gorge, but, because of the steep dip, prospecting is more difficult.

The Hawks Crag Breccia in the Waitahu River area (Fig. 7) consists of alternating beds similar to the Blackwater facies and Tiroroa "B" facies in the Buller Gorge district. Bedding is indistinct, except in places where sandstone bands occur. Slight radioactivity (twice background) has been detected in some of the beds of the Tiroroa facies.

South of the mouth of the Fox River (Fig. 1), Hawks Crag Breccia outcrops for a distance of about 15 chains (Fig. 8). The strike is 300° to 340°, and the dip 20° to 25° to the north-east. At the south end of the exposure, in leached arkosic breccia immediately beneath the unconformity below the Tertiary, are carbonaceous streaks and lenses giving counts up to 0·2 to 0·3 R/hr. The relationship of the radioactivity to the leaching has not yet been determined.

ORIGIN OF THE URANIFEROUS DEPOSITS

The origin of the Buller Gorge uraniferous deposits is uncertain, the available evidence admitting of several interpretations. The two main hypotheses are:

(i) Origin of the uranium from dispersed sources in the clastic arkosic sediments of the Tiroroa facies, the concentration being effected by circulating ground waters during the deep burial and consolidation of the sediments.

(ii) Origin of the uranium from hypogene hydrothermal solutions derived from lamprophyres or porphyries, or from both.

Both these hypotheses postulate low temperature "hydrothermal" mineralization by epigenetic solutions prior to the final consolidation of the beds. In support of the first hypothesis, favoured by one of the writers (A.C.B.), are the known deep burial of about 15,000 ft (Wellman, 1950) and the ready leaching of uranium from granitic rocks. It is

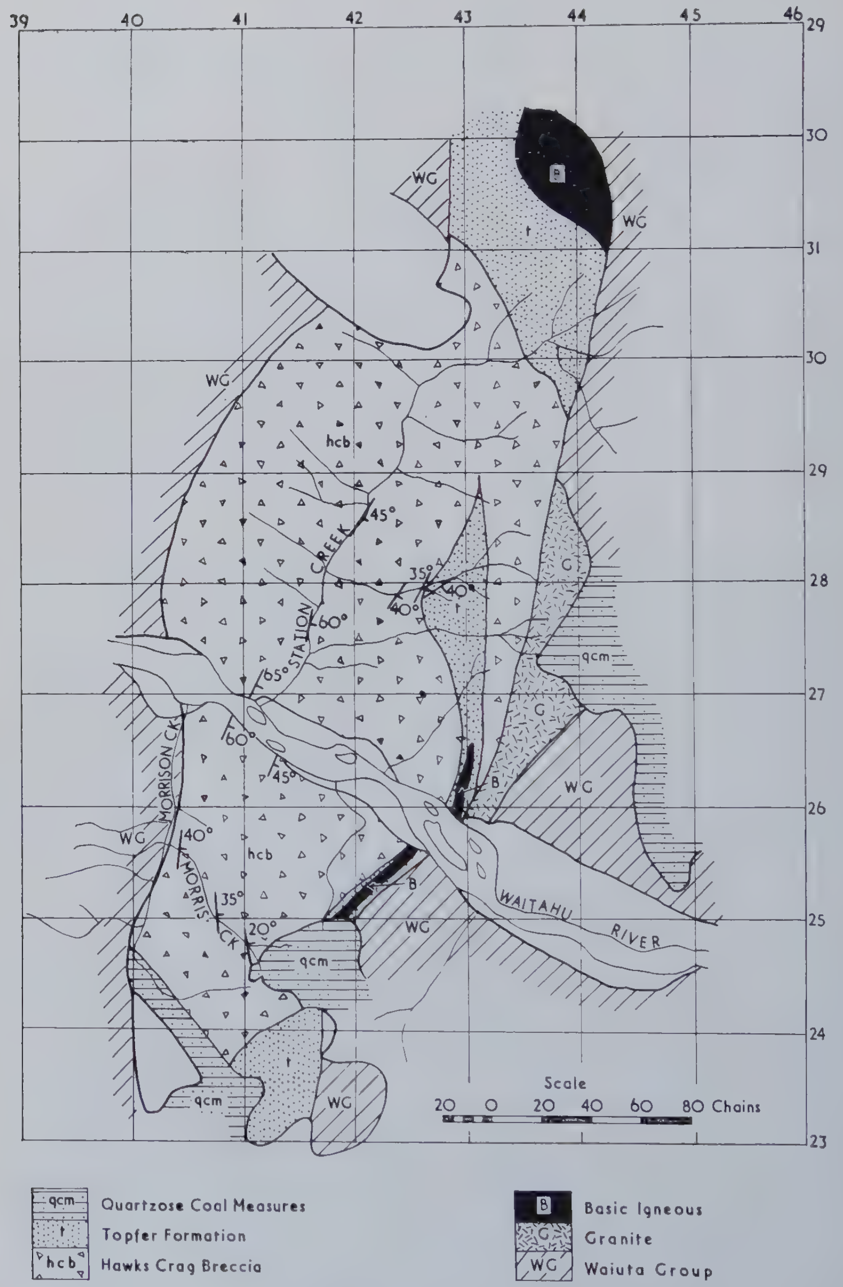

FIG. 7.—Detailed geological map of Waitahu Creek area (see Suggate, 1957).

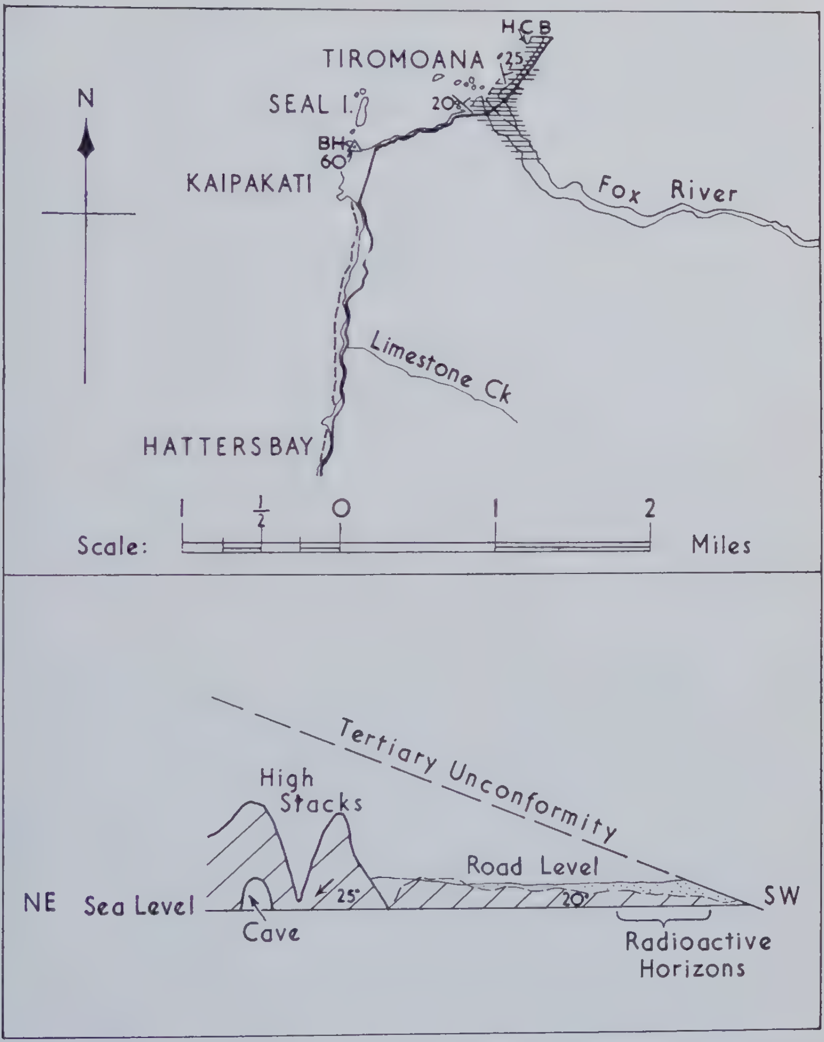

FIG. 8.—Sketch map and section showing distribution of Hawks Crag Breccia at Fox River mouth.

admitted that some of the carbonate could have emanated from lamprophyres. A corollary to this hypothesis is the interpretation of the Batty Creek "lode" as a permeable channel connecting Tiroroa facies A and B, and of the lodes and veinlets in granite gneiss and Greenland rocks as due to downward-migrating solutions in fault and breccia zones.

The alternative hypothesis, favoured by another of the writers (J.J.R.), is supported by the adequacy of the porphyries and lamprophyres as hypogene sources, the close association of hematite staining with the bedded deposits, as is the case with nearly every uraniferous vein deposit (McKelvey, Everheart, and Garrels, 1955, p. 484), interpretation of the Batty Creek "lode" as due to ascending late magmatic solutions, the absence of thorium or of resistant thorium-bearing minerals, the known occurrence of coffinite in hydrothermal veins, and the abundance of ferroan dolomite both in the bedded deposits and in the lamprophyres. The minor deposits in granite gneiss and Greenland rocks are also considered to have a hypogene origin, although whether they are coeval with the bedded deposits remains to be proven.

It is hoped that future studies will determine which of these hypotheses is the correct one. Probably both are correct in part.*

COMPARISON WITH COLORADO

Mineralization in the lower Buller Gorge shows many similarities with that on the Colorado Plateau, where the close age counterpart to the middle (?) Cretaceous Hawks Crag Breccia is the upper Jurassic Morrison Formation.

The major points of similarility of the two areas are:

(1) Bedded nature of ore deposits.
(2) Non-marine origin of host rocks in which carbonaceous material is abundant.
(3) Essentially arkosic character of host rocks.
(4) Coffinite as a primary ore mineral.
(5) Carbonate (calcite-dolomite) forms major part of gangue in unoxidized primary ore.
(6) Pyrite is associated with ore.
(7) Fluorite is found in some of the deposits.
(8) Porphyries, lamprophyres, volcanic ash beds, and uraniferous hydrocarbon are found in the "uranium province".

The differences between the two areas are:

(a) Vanadium has not been found in significant amount in the Buller Gorge rocks, in contrast with its importance in many of the Colorado ore deposits.
(b) Uraninite, a common associate with coffinite in Colorado, has not been identified in the Buller Gorge ores.
(c) The abundance of secondary uranium minerals in the Colorado Plateau contrasts with their comparative paucity in the Buller Gorge. This contrast is probably explained by the significant differences in topography and climate.

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*The more recent discovery, by prospectors of Buller Uranium Ltd., of radioactive boulders in the Big River area strengthens the first hypothesis.

(d) The close association of red hematite staining with mineralization in the Buller Gorge contrasts with the characteristics of the Colorado Plateau, where the rocks immediately enclosing the ore bodies are not red in colour, although the ore-bearing formation may be red away from the ore deposits.

ACKNOWLEDGEMENT

The writers wish to record their grateful appreciation of the assistance and hospitality received from Buller Uranium Limited during the course of these investigations, in particular for the co-operation of Mr K. E. Bullen, chief prospector of Buller Uranium Limited, who gave generously of his time in accompanying Survey officers in the field. Appreciative acknowledgement is also made of confirmatory mineralogical determinations and assays by the Atomic Energy Division of the Geological Survey of Great Britain, and for assistance and discussions in the field by Mr K. E. Beer of that Division.

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A NOTE ON THE FORMATION OF NATIVE IRON AND OTHER EFFECTS ASSOCIATED WITH CONTACT OF BASALT AND CARBONIZED WOOD AT AUCKLAND, NEW ZEALAND

By E. J. SEARLE, University of Auckland

(Received for publication, 5 May 1958)

Summary

The basalt surrounding a tree mould in a flow from Mt. Wellington, Auckland, has been found to contain native iron produced by reduction of ore. Shrinkage cracks in the charcoal within the mould have been invaded by an alkali-rich residuum of the basalt, thus providing a small-scale example of "filter-press" differentiation.

INTRODUCTION

In the course of quarrying basalt of a flow from Mt. Wellington, at Penrose, near the city of Auckland, the mould of a tree was encountered. The mould, which was near the edge of the flow, was an almost cylindrical hole in a vertical position, 18 inches in diameter, and extended from the floor of the quarry to a depth of 14 ft. A noticeable draught of air up the hole suggested the presence of an open cavity at the base of the flow.

In places the mould was occupied by charcoal formed by the destructive distillation of timber by the heat of the lava, and exhibited the usual network of shrinkage cracks produced as a result of contraction of the wood during its transformation to charcoal. These fractures were occupied by a reticulated system of veinlets of lava penetrating the charred timber (Fig. 1). Elsewhere, the charcoal had disappeared, leaving behind a cellular skeleton (Fig. 2) built up of the basaltic septae similar to those described by Bartrum (1925; 1946). In the hope of detecting evidence of reaction between the charcoal and the minerals of the lava, thin sections were cut from the basalt exposed elsewhere in the quarry, from basalt close to the mould, and from the veinlets in the charcoal. Later, polished sections were also examined and samples of minerals extracted with a hand magnet were examined thermomagnetically.

N.Z. J. Geol. Geophys. 1: 451-8.

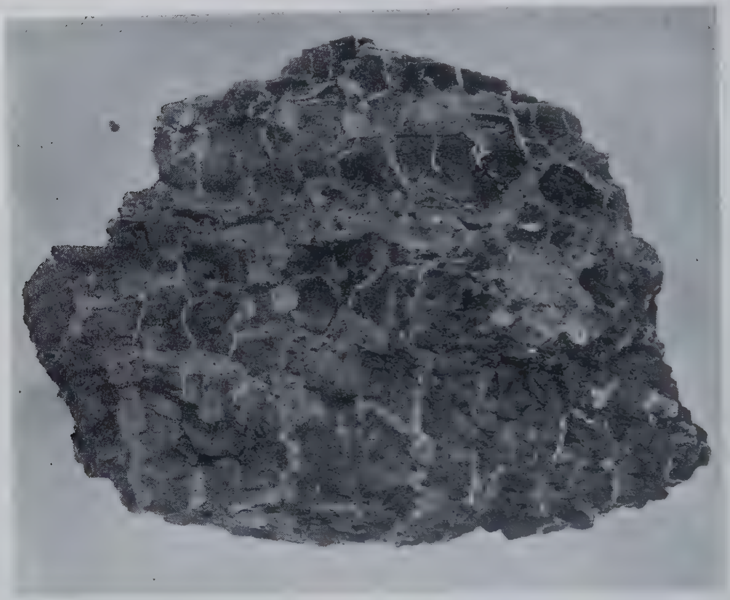

FIG. 1.—Sample of charcoal with shrinkage cracks filled with light coloured basaltic material. The width of the specimen is 9 inches.

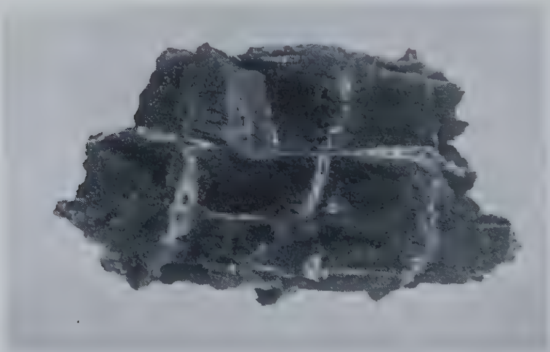

FIG. 2.—Cellular skeleton of rock septae formed in the shrinkage cracks of charcoal. Specimen is 2½ inches wide.

The basalt normal to the flow is similar to that occurring widely in the Auckland volcanic field—an olivine-titanaugite basalt with abundant iron ore and rare apatite as accessories; occasional flakes of biotite are also present. The olivine is in large euhedral phenocrysts, commonly 1·5 to 2 mm. in length, in the thin sections, but up to a centimetre in longest dimension in some of the hand specimens. 2V is positive and ranges in value from 82° to 90°, indicating a composition rich in magnesium of the order Fo_{80-90}. Titanaugite occurs both as euhedral phenocrysts (up to 1 mm.) and as rather granular micro-phenocrysts. They are a purplish brown rather pale in colour and, where zoned, the darker zone is the outer; the granular material is usually dark—both are pleochroic. Optical data are not quoted; as in the case of titanium bearing augites reliable tables showing variation of optical properties with composition appear to be lacking. Phenocrystal plagioclase (approximately An_{50}) is in laths up to 1 mm. in length and the groundmass appears to be feldspar of low 2V and low r.i.—probably potash-oligoclase. The iron ore, presumably magnetite, is strongly magnetic and occurs in euhedral crystals and aggregates up to 0·2 mm. in diameter (Fig. 3). A chemical analysis of basalt from the same flow and not far distant from the site is tabulated below, together with a modal analysis obtained from measurements made with a point-counter.

SiO_2	44·8
Al_2O_3	15·1
Fe_2O_3	1·6
FeO	10·3
MgO	10·4
CaO	10·1
Na_2O	3·4
K_2O	1·3
Li_2O	—
H_2O + 110°	0·45
H_2O — 110°	0·05
TiO_2	2·18
P_2O_5	0·62
MnO	0·20
CO_2	tr
	100·9

Ba 0·01; Sr 0·04; V 0·02
Cr 0·05; Ni 0·03.

Analysis by J. A. Ritchie, Dominion Laboratory, D.S.I.R

NORM		
Or	7·7	50·01
Ab	5·62	
An	21·85	
Ne	14·84	
Di	19·16	49·97
Ol	24·90	
Mt	1·65	
Il	2·98	
Ap	1·28	

MODAL ANALYSIS	
Fsp	40·8
Pyr	34·4
Ol	18·0
Ore, etc.	6·8
	100·0

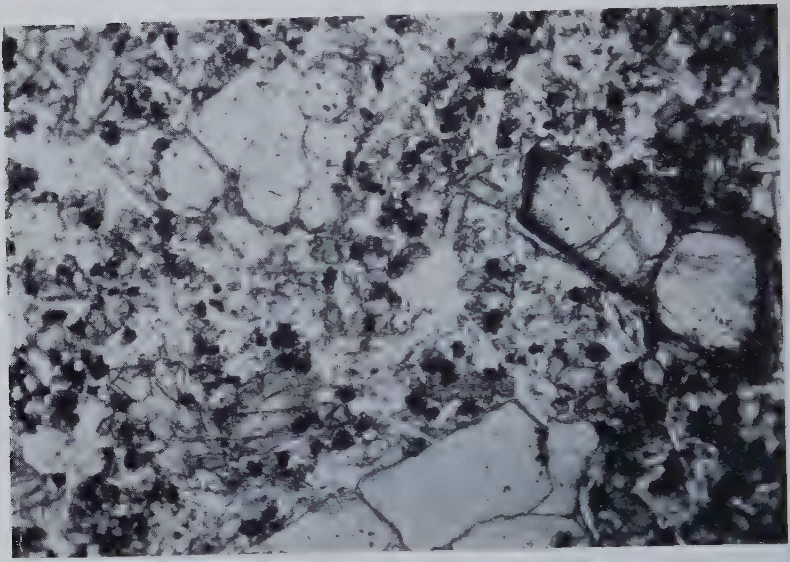

FIG. 3.—"Normal" basalt from the quarry at Penrose showing euhedral iron ore distributed evenly throughout the section. × 60.

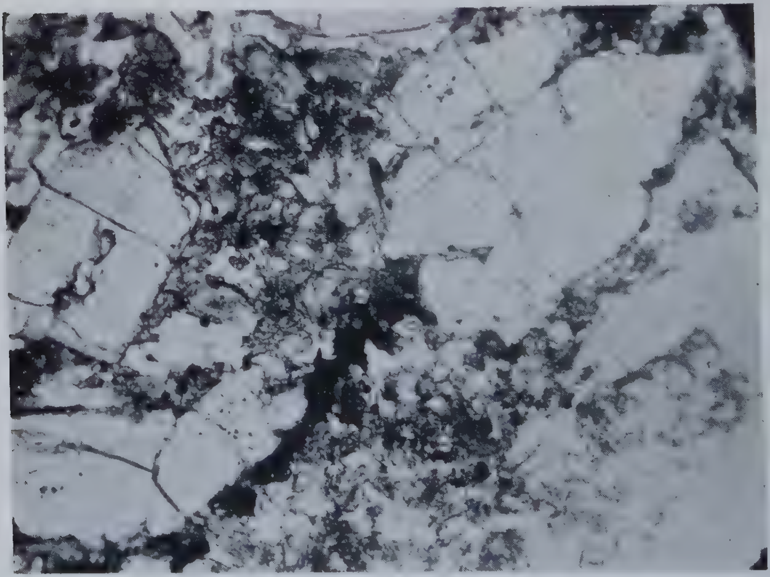

FIG. 4.—Basalt from close to the tree mould. The string of opaque mineral is native iron altered on the outside to oxide. × 60.

In the sections cut from the basalts close to the charcoal (Fig. 4) it is noticeable that the ore has adopted a habit very different from that in the normal basalt. Instead of the squarish and chunky bodies common in the latter the ore here occurs in strings of platy or wiry blebs and is highly reflecting. In some cases the highly reflecting ore is surrounded by a broad zone of dark ore. Under the microscope plates of the opaque mineral were found to effervesce with dilute hydrochloric acid. Examination of polished sections strengthened a conviction that the material of marked reflectivity was native iron and this determination was confirmed by Dr J. F. Lovering of the Research School of Physical Sciences, the Australian National University. A small sample of magnetic material extracted by a powerful hand magnet from the veinlets in the charcoal was studied thermomagnetically by Mr L. G. Parry who found that 93·8% by weight of this sample was non-magnetic—mostly charcoal with some silicate, etc.—about 6% consisted of iron oxides, probably magnetic, in which Fe^{3+} had been partially reduced by the carbon and which converted to magnetite during heating. Something like 0·2% consisted of fairly pure iron metal phase. Sections cut from the basalt close to the tree mould showed very much more native iron than did those cut from the veins but magnetic samples extracted from the former source were destroyed in transit. The microphotograph (Fig. 4) shows some of the larger stringers of native iron in the basalt of the mould.

There can be little doubt that the native iron in this material has been produced by reduction of iron in crystallized magnetite or of ferric ions in the lava. This may have been brought about either by the carbon of the charcoal or more probably by hydrocarbons distilled from the wood of the tree. Wood gas contains large quantities of methane (Karrer, 1950, p. 35) which is stable at 700° C but is largely dissociated to carbon and hydrogen at 1,000° to 1,200° C (Feiser & Feiser, 1950, p. 47). The temperature of the lava through which these gases would pass would be sufficieent to bring about a ready dissociation and facilitate the reactions:

$$Fe_3O_4 + 4H_2 = 4H_2O + 3Fe$$
$$Fe_3O_4 + 4C = 4CO + 3Fe$$

If the iron were produced in this way it would explain the greater concentration of the native metal in the basalt close to the mould rather than in the veins penetrating the charcoal. There is, however, another factor that could be responsible for the small amount of iron in the veins, as will be shown later.

Native iron has only rarely been reported as occurring sparingly in basalts. The most notable occurrence is that of large masses of iron found at Ovifak (Uifac) on the island of Disko, West Greenland, in the basalt that breaks through Tertiary beds containing coal. There is, however, some doubt as to the origin of this iron which contains 2% to 3% nickel and 3% carbon, which Lindgren (1928) considers makes it likely that the metal was carried up from some deep-seated source. There is no doubt as to the origin of the iron in the present case and its clear association with timber involved by the lava may serve to indicate its mode of origin in small quantities in other occurrences.

Lastly, with regard to the basalt near the mould, it will be noticed from the microphotograph (Fig. 4) that, unlike the normal basalt, there is no phenocrystal feldspar. This is often found to be the case near selvedges in the local basalts. It is likely that rapid cooling of the basalt was induced by the passage through the lava of gases distilled from the green timber.

The rock constituting the septae of the lithic skeleton of shrinkage cracks in the charcoal is light-grey to whitish in colour. Thin section examination shows that it contains no olivine and remarkably little ore.

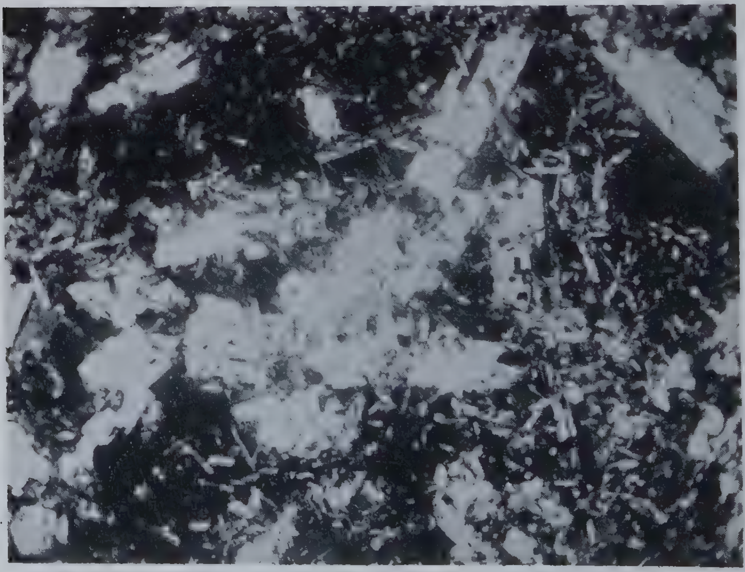

FIG. 5.—Section of the light coloured rock of the septae in the charcoal showing acicular titanaugite enclosed by coarse-grained plagioclase. Crossed nicols, × 60.

The pyroxene that occurs is quite different in appearance from that in the basalt outside the cast, occurring as it does in slender needles which are markedly pleochroic (purplish grey to mauve) and occasionally slightly greenish. They are often set in patches of light-brown cryptocrystalline material that appears to represent devitrified glass. The texure of the rock is very different from that of the normal basalt—much shows a pegmatoid texture formed by coarse-grained plagioclase of low refractive index enwrapping eelongated phenocrysts of euhedral titanaugite. Minute needles of soda-rich reibeckitic amphibole are formed along the contact of the vein and the charcoal. Rod-like bodies of reasonably high reflecting power occur scattered in the septae, particularly near the contact. Some of these may be ore but others seem rather to be carbonized plant tracheids. Felted masses of tracheids changed to a cryptocrystalline yellowish-brown product were found in the charcoal but generally elements of the timber have been completely carbonized. The apparent absence of ore may be due to the formation of iron in contact with the charcoal enclosing the veins, for many of the carbonized wood elements are attracted by a hand magnet.

It would appear that the material that penetrated the narrow crevices of the network of shrinkage fractures represents the residual liquid of the basalt. None of the early-formed minerals has been able to gain access and the rocky skeleton of the shrinkage cracks therefore lacks the olivine, the first generation pyroxene, and the ore constituents. Many of the septae are of greater diameter than that of much of the phenocrystal material of the basalt but they may well have been fed by smaller cracks. It is likely, too, that the lava encompassing the timber was still in a highly fluid form and the fluidity may well have been increased by the volatiles distilled from the wood. Certainly the second generation pyroxene could not have separated, for it was of a size that could well have been accommodated within the small fissures in the charcoal, and besides, the residual liquor still contained the necessary ions for the formation of pyroxene which has separated in longer crystals than was the case in the groundmass of the basalt. It would seem that phenocrystal feldspar had already separated, for the plagioclase of the veins seems to be wholly of potash-oligoclase. The presence of the soda amphibole, together with the titanaugite and the occasional greenish pyroxene, points to an alkali-rich residuum with significant iron and titanium, as the parent of the rock forming the veinlets.

By and large the occurrence provides a very nice example on a small scale of the operation of differentiation by "filter-press" action.

ACKNOWLEDGEMENTS

The writer is indebted to Dr J. F. Lovering, Research School of Physical Sciences, the Australian National University for the examination of material; to Professor R. H. Clark, University of Wellington, for preparing plastic mounts; to Directors of the New Zealand Geological Survey and of the Dominion Laboratory for analysis of the basalt; and to his colleague, Dr R. N. Brothers, for discussion of the problems involved.

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REPORTS OF A SUBMARINE ERUPTION OFF NEW ZEALAND IN 1877

By D. R. Gregg, New Zealand Geological Survey, Department of Scientific and Industrial Research, Christchurch.

(Received for publication, 2 April 1958)

Summary

Submarine eruptions were reported on 1 December 1877 near East Cape. They were probably not of volcanic origin, and may have been a tsunami.

During the compilation of a list of eruptions of the Tongariro National Park volcanoes, reference has repeatedly been found to a submarine eruption off the east coast of the North Island in December 1877 (Anon., 1878, p. 370; Rudolph, 1887, p. 359; Suess, 1909, p. 301; Sapper, 1927, p. 337; Van Padang, 1938, p. 91). These references appear to be based on the same observation. The earliest reference (Anon., 1878)* has been translated as:

> Capt. Helander, of the Steamer "Go-Ahead", on the way from Gisborne to Auckland, observed on 1 December 1877 between 8 and 9 hours, about 5 sea miles from Open Bay, a submarine volcanic outbreak. The sea foamed up enormously and rocked the ship with a strong swell. At the same time earthquakes were felt at Gisborne.

An independent reference to a similar disturbance observed from a ship off East Cape on the same day, is given in the *Canterbury Times* for Saturday, 8 December 1877. The report was received by telegraph on 3 December.

> After the arrival of the Pretty Jane today from Gisborne, it became known that she had been subject to a strange experience on Saturday evening, between eight and nine o'clock. She was then steaming for Auckland, and was about five miles seaward from East Cape, when the mate observed, some distance ahead, approaching the steamer's bows, in a slanting direction, a strip of seething and excessively agitated water. Looking outwards, he saw a long streak of similarly agitated water. The belt of disturbed water was less than a quarter of a mile broad, and approached the steamer faster than she was steaming. There were no heavy waves, but the water appeared as if boiling in a cauldron. The steamer's course was altered to avoid the agitated stream approaching, and

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*This is evidently based on an item in *Globus, 34 (1)* : 16, 1878, that is not available to the writer.

N.Z. J. Geol. Geophys. 1 : 459-60.

> just escaped it, but the vessel was then tossed and pitched about in a most wonderful manner, and the passengers aboard believed she was foundering. After a time the tossing ceased, and the steamer got into smooth water. The cause of the commotion is unknown but it was probably some subterranean volcanic action. On Friday evening, or early on Saturday morning, a slight earthquake was felt at Gisborne, and whether the phenomenon observed by those aboard the Pretty Jane arose from the cause that produced that earthquake or not, no one on board is able to say.

It seems very unlikely that the reports refer to a volcanic eruption. The disturbances of the sea took place at about the same time some 25 miles apart. It seems probable that the phenomenon was a tsunami resulting from submarine landslides or faulting connected with the earthquake felt at Gisborne. Other tsunami have resulted from earthquakes on the east coast of the North Island (Laing, 1954).

ACKNOWLEDGEMENTS

Thanks are expressed to Mr B. W. Collins, New Zealand Scientific Office, London, for making extracts from publications not available in New Zealand, and to Dr E. W. Bennett, Department of Scientific and Industrial Research, Christchurch for assistance with translation.

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SUBMARINE GEOLOGY OF BLUFF HARBOUR

By B. L. Wood, New Zealand Geological Survey, Department of Scientific and Industrial Research.

(Received for publication, 27 May 1958)

Summary

In a small area at the southern end of Bluff Harbour, which has been explored by submarine drilling, a thin sequence of moderately compacted late Tertiary terrestrial and estuarine beds rests on a basement of Paleozoic intrusive and metamorphic rocks, and is overlain by uncompacted Recent estuarine sands. The basement rocks are decomposed to a depth of 45 ft beneath the Tertiary beds which also have undergone a similar type of decomposition with leaching. The Tertiary beds are Taranakian or lower Wanganui in age (upper Miocene to Pliocene).

INTRODUCTION

In 1953, the writer collaborated with engineers of the Bluff Harbour Board and the Graham Drilling Company on sub-surface investigations for foundations for proposed new harbour works. Through the courtesy of Mr D. E. S. Mason, Chief Engineer of the Harbour Board, all relevant drill-logs, cores, specimens, plans, and cross-sections were made available to the writer. The plans and sections originally prepared by Mr W. Sparrow, of Graham Drilling Company, were redrawn for this paper and slightly modified.

The writer examined most of the drill-cores during or before the testing of various samples by the Soil Bureau, D.S.I.R., and assigned the lithological names and descriptions used herein. Small portions of particular cores were obtained for petrological and microfloral study.

PREVIOUS GEOLOGICAL WORK

Apart from a manuscript report by Mr A. C. Beck, New Zealand Geological Survey, on the nature of the rock at the entrance of Bluff Harbour, no work had previously been done on the submarine geology.

Service (1937) described the geology of Bluff Peninsula and summarized the observations of previous geologists.

N.Z. J. Geol. Geophys. *1* : 461-9.

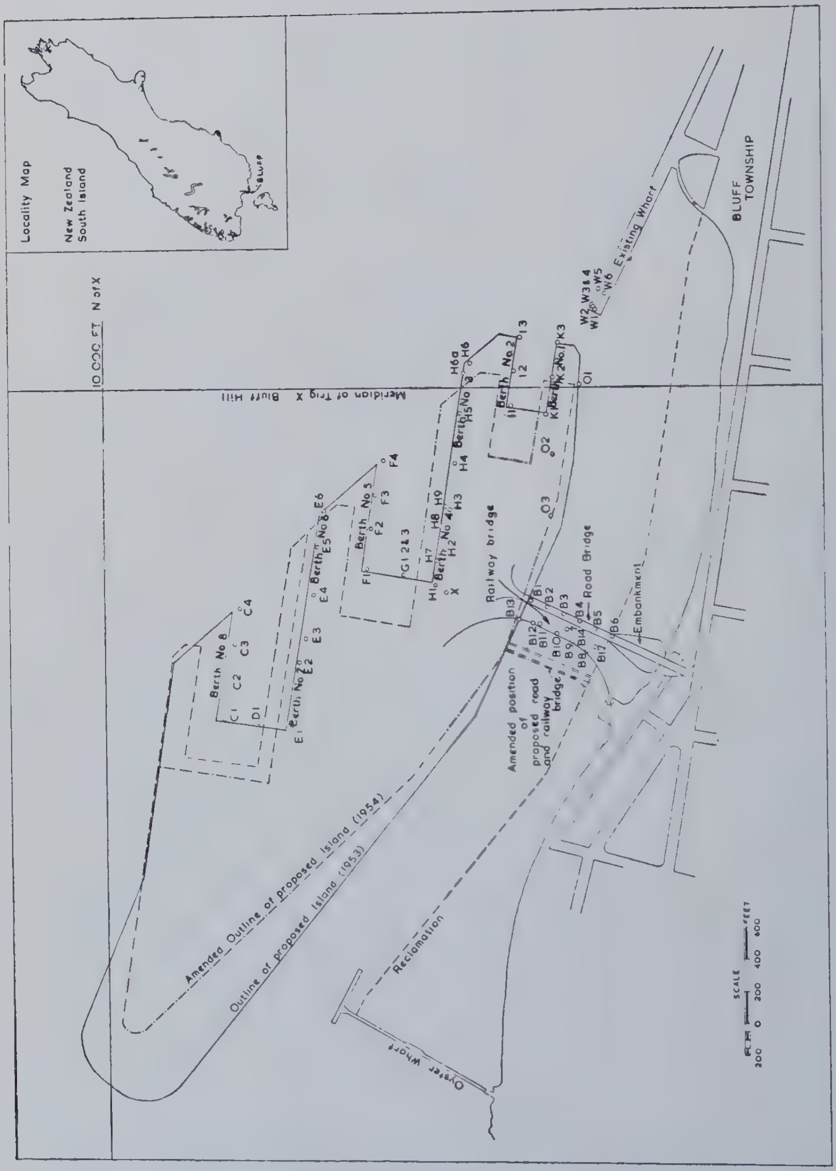

FIG. 1.—Present and proposed wharf layout and drill sites, together with locality plan.

SUMMARY OF ADJACENT GEOLOGY

Bluff Peninsula consists of volcanics invaded and metamorphosed to varying degrees by plutonic rocks. In Bluff Hill the plutonic rocks are mainly norite, but elsewhere in the peninsula they include granite, diorite, gabbro, pyroxenite, and peridotite.

The metamorphic rocks crop out in narrow strips at the Bluff wharves and on the foreshore nearby, at Te Waewae Point across the harbour entrance, and along the west shore of the harbour. The rocks are dark-grey and light green-grey or yellowish green, at most places strongly banded, and commonly weather out in angular blades and slabs. The banding and foliation most commonly strike north-north-west and dip steeply west-south-west.

The present south-west shoreline of Bluff harbour follows closely the contact between the intrusive and metamorphic groups, and presumably the latter underlie most of the harbour. According to Service's geological map (1937, facing p. 186), a small part of the harbour between the oyster wharf and the main wharves is underlain by norite.

STRATIGRAPHY

Rocks and deposits within the harbour basin are, the intrusive and metamorphic rocks of Bluff Peninsula which constitute the basement for the younger deposits, a sequence of slightly compacted late Tertiary sandstones, muds, and clays, at least 30 ft thick, and a Recent fill of estuarine and marine loose sands, pebbly sands, and muds, up to 50 ft thick. They are distinct in age, lithology, and compaction.

The basement rocks are, by correlation with similar rocks elsewhere in Southland, late Paleozoic in age. Wherever the basement rocks are overlain by Tertiary beds, they are much decomposed, at one place to a depth of at least 45 ft (drill-hole H3, Fig. 1). The decomposed zone varies in thickness, probably as a result of the original irregularities of the basement surface, and resembles decomposed or "leached" zones in basement rocks beneath Tertiary cover elsewhere in New Zealand, although the degree of leaching is not so great. At Bluff the entire zone retains some of its original colour, being mainly dark-green to green-grey, and much of the original rock structure can be seen in undisturbed core-samples whereas in other New Zealand localities the upper parts of the decomposed zone are strongly leached to white siliceous clay. A sample from drill-hole F3 exhibits an irregularly white-spotted appearance in a dark-green background, which suggests the original structure of a coarse plutonic rocks such as that of the norite occurring nearby onshore immediately west of the main wharves. In other samples there are bands 5mm to 20mm wide of dark green, light brown, and light yellow, that resemble those in the metamorphic rocks exposed along the foreshore south-east of the wharves. The decomposed rock usually has the consistency of a tough sandy clay when wet, and can easily be broken by hand when dry.

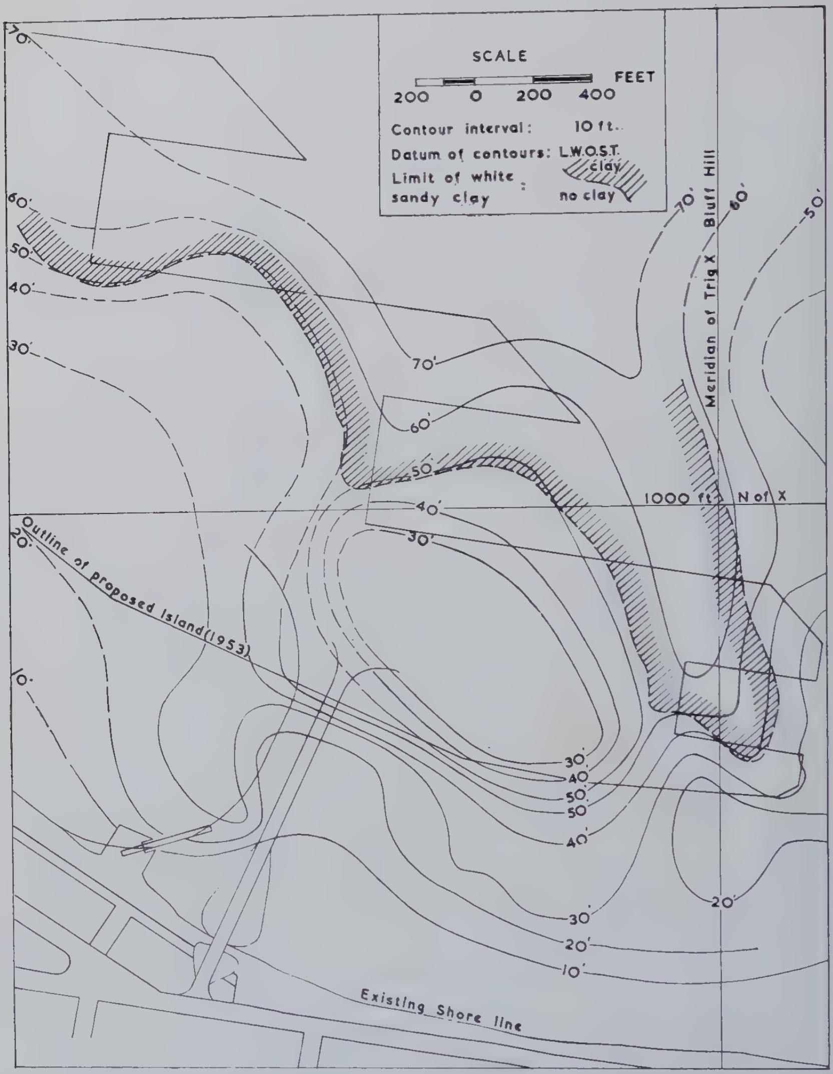
SCALE
200 0 200 400 FEET
Contour interval: 10 ft.
Datum of contours: L.W.O.S.T.
Limit of white sandy clay: clay no clay
Meridian of Trig X — Bluff Hill
1000 ft N of X
Outline of proposed Island (1953)
Existing Shore line
70'
60'
50'
40'
30'
20'
10'

FIG. 2.—Plan showing contours drawn on upper surface of decomposed rock, together with the limits of white sandy clay.

The degree of decomposition decreases with depth and the decomposed rock passes gradually down to fresh hard rock. The configuration of the upper surface of the decomposed rock, which is also the base of the Tertiary sediments, is shown in Fig. 2. This illustrates the

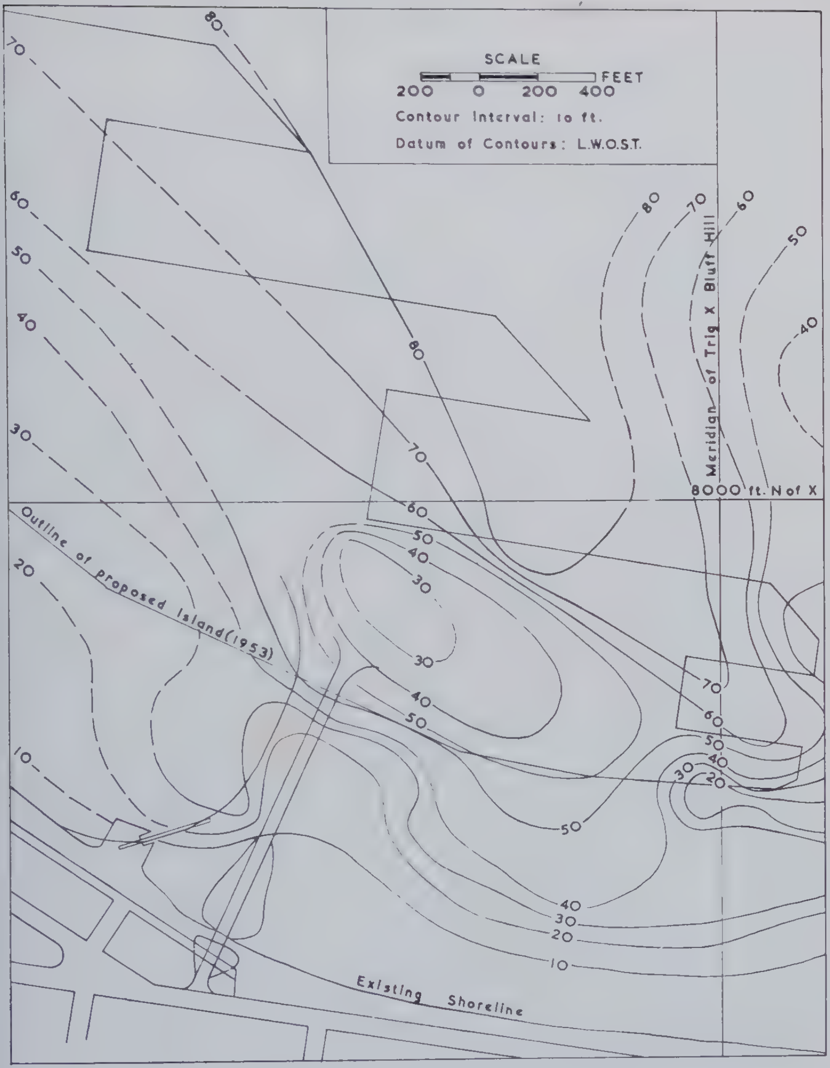

FIG. 3.—Plan showing contours on interface between decomposed and fresh rock.

positions of the gentle rises and hollows of the original Tertiary deposition surface. For comparison, the shape of the surface of the hard rock is shown in Fig. 3.

The Tertiary beds are markedly lensoid, the most persistent lens being one of white sandy clay which was penetrated in most drill-holes (Fig. 4).

As shown in the sections (Fig. 4) the lens of white sandy clay is commonly the lowest bed and rests on decomposed basement rock with a sharply defined contact, but here and there it is underlain by moderately compacted and cemented brown-grey sandstone at least 10 ft thick (Sst in legend, hole H5), and deep-blue silty, pyritous mud, 3 to 4 ft thick (hole F2). The full extent of the white sandy clay cannot be determined from the drill-logs, and the known boundary is shown in Fig. 2 by the broken line bordering the hached area. It is evident that the bed lies on the edge of a gently undulating basin and may well extend for some distance north and east of the explored areas. In all but colour the clay resembles the decomposed rock beneath; it is tough when wet, easily crumbles when dry, contains small amounts of fine siliceous grit, and exhibits a blotched surface of pale grey and white. The white spots, which are commonly 1 to 4mm and irregular, appear to represent original feldspar grains. The grey material surrounds the white spots like a matrix and in it a very few flakes of mica can be seen. The appearance is that of a transported sediment and not a residual deposit, and indicates that the clay was formerly a coarse feldspathic sand undoubtedly derived from the neighbouring intrusive and metamorphic rocks and deposited under terrestrial conditions.

Further evidence of the depositional origin of the clay is the occurrence beneath it of beds of brown-grey sandstone (drill-hole H5), a thin bed of pyritic mud (drill-hole F2), and the presence within it of a few dull carbonaceous and bright coaly streaks. The streaks probably represent odd fragaments of wood and thin layers of much decomposed plant debris. No recognizable plant macrofossils were seen. The core-samples of white clay commonly split along numerous steeply dipping slickensides.

Mr J. J. Reed, Petrologist, New Zealand Geological Survey, reports as follows on samples submitted for analysis: "X-ray examination and thermal analysis by Dr M. Fields, Soil Bureau, showed that the white clay is a good sample of kaolinite. Moreover, the material does not change colour on ignition, indicating that the iron content is low. A thermal analysis by Mr I. McDowall of the Pottery and Ceramic Research Association confirmed that the main constituent is kaolinite, probably more than 70%."

Above the white sandy clay are sediments, as shown in Fig. 4 (berths 5, 6, 7, and 8) consisting mainly of compacted blue-grey, brown, and black silty sands. The darker sediments contain fragmentary plant remains and pollens, and usually contain more clay than the enclosing sands. In drill-hole F2, 2 ft of pebbly sand lies on the sandy clay; this is the coarsest Tertiary sediment found in the area. The pebbles are derived from local rocks.

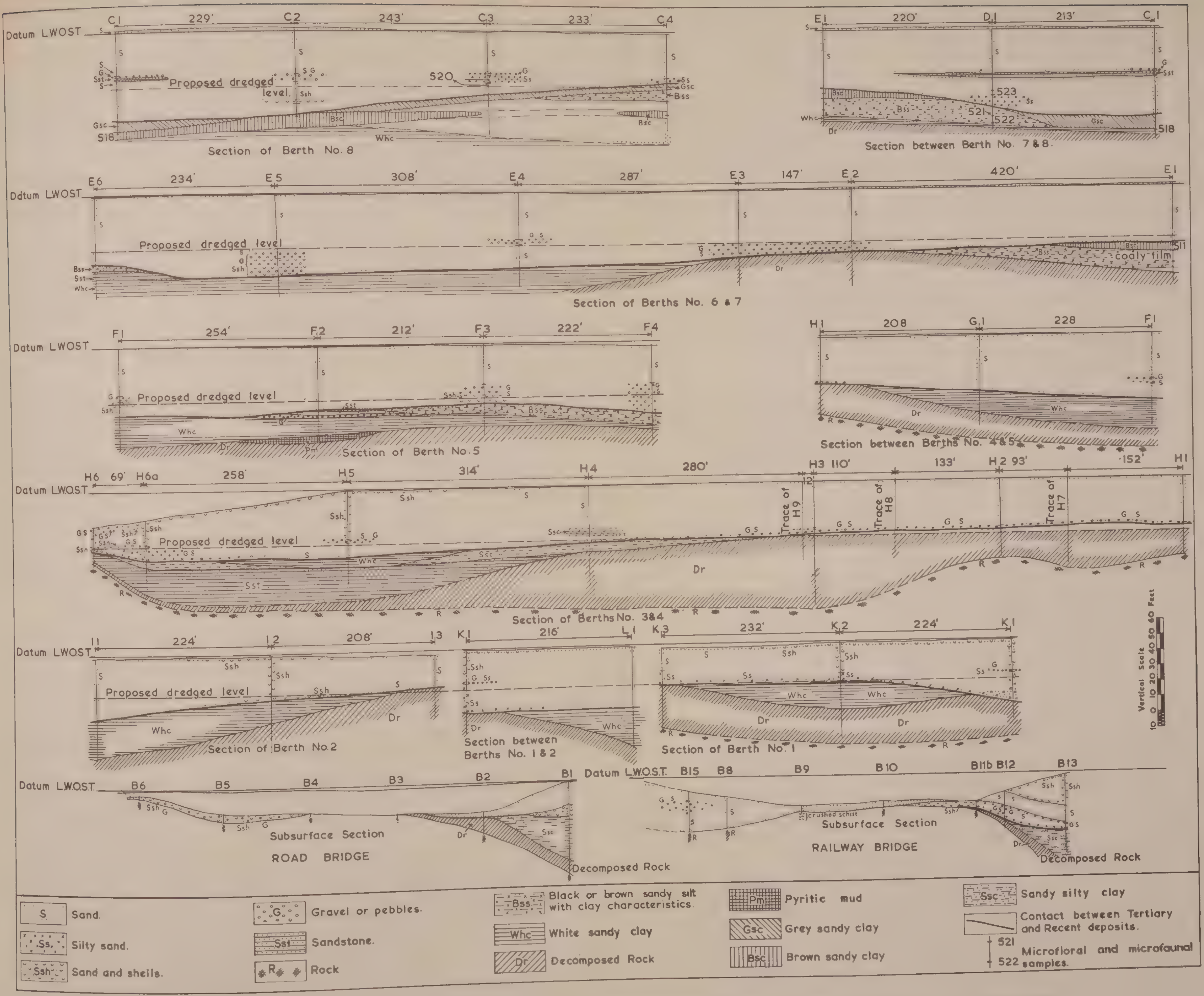

FIG. 4.—Sections along lines of drill-holes (see Fig. 1) showing geology based on core information from drill-holes. Proposed dredging depth is also indicated.

The extreme shoreward margin of the Tertiary deposits has been explored by closely spaced lines of drill-holes (B1 to B13) along the proposed sites of the road and rail bridges (Fig. 1). The near shore drill-holes revealed loose Recent sands and gravel resting on a fairly fresh surface of intrusive and metamorphic rocks. At the other end of the lines of holes, compacted sandstone was found beneath the Recent deposits, resting on a zone of weathered rock. The sandstone must constitute an isolated lens, for the nearest drill-holes (H1-4, and C1) penetrated only decomposed rock or white clay.

The Recent sediments are a normal estuarine assemblage of intergrading beds of uncompacted pebbly, shelly, and silty sands, blue-grey in colour and somewhat foetid when fresh. A 2 ft bed of somewhat compact sand (termed "sandstone" in the drill-log) was encountered in drill-holes C1 and D1.

Apart from the obvious shelly beds, many of the Recent sediments are slightly calcareous, and two samples (S.182/520 and 523) were examined by Mr N. de B. Hornibrook, Micropaleontologist, New Zealand Geological Survey. Sample 520 contained the Foraminifera *Patellina corrugata*, a few Polyzoa, and fragments of *Arachnoides zelandiae* Gray, the cake-urchin or snapper-biscuit which has its first known occurrence in the Waiauan Stage but is common only from the Waitotaran Stage to Recent. The foraminifer ranges from Kaiatan to Recent. Sample 523 contained only fragments of *Arachnoides zelandiae*.

TERTIARY STRUCTURE

It is highly unlikely that any of the Tertiary beds have been folded, and the present structure is believed to be the result of initial dip, probably slightly accentuated by moderate compaction. Dip angles are all small, ranging from 0° to 6°, with a slightly steeper dip of 16° indicated between drill-holes H6 and H6a.

Within the explored area, the Tertiary beds generally constitute an irregular sheet, thinning out to the south-west on the rising basement rock and thickening north-east towards the harbour basin, with a narrow channel-filling prolongation extending south-east towards the main wharf. They are probably only the marginal part of a more extensive deposit in the harbour-basin.

The occurrence of steeply dipping carbonaceous films in some samples of white clay indicates that slumping or flowage has occurred after deposition. The films dip irregularly in all directions but presumably were deposited flat. The beds may have been disturbed either immediately after deposition and while still sandy, or long after when weathered and leached to clay.

AGE AND CORRELATION OF TERTIARY BEDS

Samples of carbonaceous silts and clays were submitted to Dr R. A. Couper, Micropaleobotanist, New Zealand Geological Survey, for microfloral study. The location of the samples which are numbered S.182/518, 521, 522, is shown in the sections of Fig. 4. Dr Couper reports that the samples contained microfloras of upper Taranakian or at youngest lower Wanganuian age. The microfloras are definitely older than the Toetoes Bay submarine lignite of probable Nukumaruan age described by Couper (1951). The beds are late Tertiary in age but older than the late Tertiary Kaikoura Orogeny.

Although no similar deposits of this age are known elsewhere in Southland, lignites containing closely similar microfloras have been obtained in the Awarua-Seaward Downs area, a few miles south-east of Invercargill. These are, from a pit near Waimatua (grid reference S.182/439975), from the bed of Duck Creek (S.182/449994), and from a bore at Awarua Radio Station (S.182/372803) at a depth of 242 ft to 285 ft below the surface. These lignites are shown by microfloras to be much younger than those of the Mataura Valley and Ashers Siding which Couper (1953) states are Landon age.

The lignite in the Awarua-Seaward Downs locality is interbedded with white quartz gravels such as crop out in terraces around the north end of Bluff Harbour. The white quartz gravels also contain much kaolin clay. This assemblage has been derived from a terrain of low relief, which had been subjected to prolonged conditions of chemical weathering, and was deposited by slow moving rivers and streams. Much of the Tertiary sediment in Bluff Harbour indicates similar conditions of deposition, i.e., low relief and prolonged exposure to chemical weathering. Also, the deeply decomposed zone of basement rocks is undoubtedly the result of deep weathering without much removal of the weathering products, signifying low relief of the basement surface before the Tertiary beds were deposited.

The proximity of these two similar types of deposits, and the similarity of their contained microfloras is strong evidence that they are coeval, but the difference in their sedimentary composition, i.e., quartz gravel, and clay, obviously far-transported, probably from the Central Otago area, as against angular, locally derived feldspthic sand, indicates that the areas of deposition were separated by a barrier of some kind, possibly a now-buried ridge of basement rock beneath the upper reaches of the harbour.

It thus seems that since the late Tertiary, there has been an isolated rock-basin, occasionally estuarine, or swampy, perhaps at times even land-locked on the present site of Bluff Harbour.

ACKNOWLEDGEMENT

The writer is indebted to Mr D. E. S. Mason, Chief Engineer of the Harbour Board at Bluff, for permission to use his data.

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EVIDENCE OF LATE PLIOCENE WARMTH IN NEW ZEALAND

By C. A. COTTON

(Received for publication, 30 May 1958)

Summary

The theory of late Pliocene warmth is of some importance in explanation of Southland pedimentation and also of the deep weathering of greywackes at Wellington, where the K Surface, though of late date, may, like the "peneplains" of Tertiary ages in Europe, have been planed in a warm-humid, or "tropical" climate.

It has been suggested (Cotton, 1957, p. 787) that a pediment-like feature in the Pukerua tectonic corridor, near Wellington, may have been formed by semi-arid pedimentation in the Villafranchian, though it seems more in keeping with the known fast tempo of landscape evolution in New Zealand to assign a much later tentative date to this particular event, (Cotton, 1957, pp. 770, 787). This is more consistent also with the theory that the deformation of the land surface responsible for shaping major forms of relief at Wellington took place about the middle of the Pleistocene.

The pedimentation of the Gore district of Southland, as described by Wood (1956, p. 19), seems on the other hand to have been a late, perhaps very late, Pliocene event: it implies hot and probably semi-arid climatic conditions.

Geologists have long been accustomed to accept without criticism a theory that the temperature of the earth's atmosphere and surface declined very gradually over a period of many millions of years from the high early Tertiary maximum to the Pleistocene minimum, a theory that makes it difficult to explain pedimentation in the very late Pliocene that was presumably conditioned by atmospheric warmth. It is interesting therefore to note that evidence of late Pliocene warmth is found in Central Europe. Büdel (1957a) points out that the refrigeration which eventually replaced world-wide Tertiary warmth by the cold of the first Pleistocene ice age was startlingly sudden. "Up to the end of the Pliocene", he has written (1957a, p. 35), "in Central Europe climatic conditions prevailed which allowed active and wide development of extensive "wash plains" of the kind now developing under sub-tropical to tropical conditions ["peneplains" such as are sometimes attributed to the "savana cycle"]. . . . A climate warmer than that of today must have prevailed right up to the Pliocene; but then a relatively sudden change to the tundra climate of the earliest Pleistocene ice age took place. . . . Evaluation of Upper

Pliocene pollen analyses reveals that the forests then consisted of a mixture of Central European and evergreen trees—often to the astonishment of paleobotanists. The conclusion may perhaps be justifiable that the Upper Pliocene warm climate of Europe resembled a sub-tropical monsoon climate. . . . The climatic zones of the present day and the Polar front appear not to have been so well defined as they have been since the beginning of the Glacial Period."

In New Zealand, especially around Wellington, deep weathering under tropical or almost tropical rain-forest conditions probably continued until the sudden fall of temperature to a near-glacial level took place. Thus, the deep zone of weathered rocks beneath the K Surface at Wellington (Cotton, 1958) suggests comparison with the "two surfaces of levelling" (*doppelten Einebnungsflächen*) found by Büdel (1957b) to be the natural product of landscape evolution in the tropical savana climate, where the "soil cover" instead of being some 18 inches to 5 ft thick, as in Europe, is reported to be up to 200 ft thick (with average thickness 100 ft) on "tropical plains" (p. 223). The postulated "two surfaces of levelling" must exist as a result of divorce of the "processes of weathering and denudation". The upper surface is a subaerial very level plain, while the lower (which might also be termed the subterranean, fresh-rock surface) is described as "the front of attack of the chemical decomposition progressing rapidly to depth" (Fig. 1).

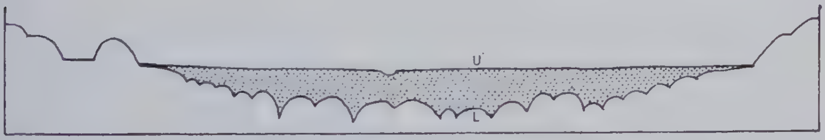

FIG. 1.—"Tropical" planation: development of "double surfaces of levelling". U: upper (subaerial) surface; L: lower (subterranean) surface at the base of the zone of weathering. Vertical scale greatly exaggerated. (After Büdel, 1957b, fig. 5/2.)

The lower surface is necessarily a very uneven one, especially on a heterogeneous terrain with rocks varying greatly in their susceptibility to chemical weathering. A general lowering of the land surface—i.e., of the subaerial plain, a smoothly level surface—may occur owing to a relative lowering of the base level due to upheaval or other cause; or, instead of such even lowering, a stripping away of weathered material may take place because of a change of climate in the direction of aridity. In either case less deeply weathered rock masses may emerge as inselbergs, for which a rational explanation is thus found (Fig. 2). Because of the domical form these assume Büdel (1957b, p. 215) has proposed to call them "shield" insel-

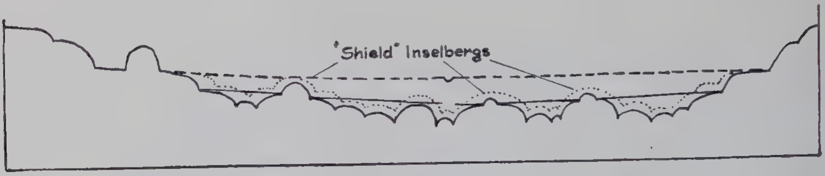

FIG. 2.—"Tropical" planation at two successive levels, the later one with isolation of "shield" inselbergs such as are found in Northern Nigeria and the southern part of Somaliland. Vertical scale greatly exaggerated. (After Büdel, 1957b, fig. 7.)

bergs. Some of the monadnocks of Central Europe are, according to Büdel, recognizably of such origin, for in that region deep weathering (necessarily of uneven depth) must have taken place beneath the surfaces of planation that were developing from time to time throughout the Tertiary and right on until the end of the Pliocene under conditions of climate like those now prevailing only in very low latitudes. Stripping away by erosion after upheaval of the thick layers of regolith formerly present above very uneven surfaces of residual bedrock accounts also for areas of apparently anomalous relief on otherwise "planed" surfaces now at high altitudes in Europe which survive from ancient times, one being the widely developed and hitherto unsatisfactorily explained *Raxlandschaft* that bevels the eastern Alps.

In New Zealand, notably in the Wellington and Hutt Valley districts, very deep weathering is common, but this is confined to the "shattered greywacke", which Stevens (1957, p. 208) has distinguished from "unshattered" rocks. There is some development of relief features that may be attributed to circumdenudational exposure of residual cores of the unshattered rocks that have formerly been at a shallow depth below the K Surface (*cf.* Cotton and Te Punga, 1955, fig. 3; Stevens, 1957, fig. 13). Some of the smaller of these seem, with a certain amount of erosional modification, to have become "round knobs" (*cf.* Cotton and Te Punga, 1955, pl. 37/1; Stevens, 1957, fig. 18; Cotton, 1958, photo 5).

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DISTRIBUTION OF POPULATIONS OF FOSSIL FORAMINIFERA

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Summary

A simple analysis of variance model is applied to the problem of assessing whether or not homogeneous populations of Foraminifera exist within a lithologic unit. Experimental results show that while for some species samples were drawn from common populations, there were others for which sampling indicated heterogeneity. This heterogeneity tended to be generated in the stratigraphic dimension and the hypothesis is advanced that this is due to differential rates of sedimentary influx. The practice of taking single samples from beds or from wide stratigraphic intervals in uniform lithologies is considered unsafe for generalizations concerning the distribution of populations within the sampling interval.

Introduction

Recent assessments of the paleoecological implications of fossil foraminiferal faunules have tended to be made on the basis of frequency counts of members of the faunule. However commendable this trend may be, consideration of the literature reveals that singularly little attention has been paid to the adequacy of the sampling schemes employed. Israelsky (1949), whose "Oscillation Chart" is based upon a foraminiferal analysis of one well, used samples of cuttings taken at 30 ft intervals over a thickness of 5760 ft. Visser (1951, p. 204) in her study of the type Maestrichtian took samples that "were in each case at about the same distance (80 cm) from each other, and I paid special attention to the pecularities of the layers from which the samples were taken." For zonal analysis of the Lower Gault of Kent, Khan (1952, p. 71) took 58 samples with a vertical interval of 6 inches. Albritton *et al.* (1954, p. 331) in analysing the Grayson Marl took samples at 5·5 ft intervals in the lower, lithologically uniform portion of the formation. In the upper part where there are many thin beds they state that " . . . samples were taken at irregular intervals in order that there might be at least one for each stratum of marl or clay between the limestone layers." Pierce (1956) used a sampling interval of approximately 15 ft in his Californian study. Finally, in the case of a Pacific core, Hamilton (1957) mentions that sampling was governed by changes in lithology.

It is clear from this survey that sampling has been carried out either on the basis of one sample from each lithologic unit or, in thicknesses of uniform sediments, at arbitrarily fixed intervals. It is apparent, however, that sampling carried out on this basis involves the assumption that a highly over dispersed condition obtains, wherein all the units of the faunule show an even distribution throughout the sampling universe. At the present stage of knowledge of the distribution of populations of fossil Foraminifera this assumption appears unjustified. It is the essential purpose of this paper to record the results of an experiment designed to test the sufficiency of this assumption.

SAMPLING DESIGN

In analysing the frequency distribution of populations of fossil Foraminifera it is desirable that measurement be made along two dimensions, geographic and stratigraphic. With census data collected on such a pattern, variance analysis may lead to isolation of the dimension causing heterogeneities within the population studied, should such exist.

The design adopted for the experiment involved a systematic grid layout of 25 sampling points, in the manner shown in Fig. 1. Study of a small trial grid used in the same sampling area showed that population variances tended to be smaller along the geographic dimension than the stratigraphic and this information decided the intervals used in the experiment; the geographic interval was set at eight inches and the stratigraphic at four inches. A grid employing these intervals was laid out from an horizon (A sampling level) lying stratigraphically 132 ft above the base of the exposed section at Bluecliffs, South Canterbury, New Zealand. This section forms the type locality for the mid-Oligocene Otaian stage (Finlay and Marwick, 1947, p. 232-3). The bed sampled consists of poorly sorted glauconitic blue-grey clayey siltstone and is one of a set termed the "banded beds" by Finlay and Marwick 1947, p. 233).

Sampling was carried out with a standard open leather punch, size 6, taking a sedimentary volume of 0·40 cc.

PREPARATION OF SAMPLES AND COUNTING

Complete disaggregation of the samples was accomplished by preliminary soaking in 0·0001N sodium hexametaphosphate followed by agitation in a standard electric milk shaker for at least three hours. The sediment was washed over a sieve with openings of 0·074 mm nominal diameter. As this technique resulted in breakage of some specimens, census procedure was standardized by counting as a single occurrence every recognizable specimen of the population being studied.

To minimize the effects of possible operator error, procedures for the collecting and preparation of samples were rigorously standardized, and this source of error has not been further investigated.

To assess the magnitude of the counting error, a replicate count was made of the grid for *Sphaeroidina bulloides* d'Orbigny. From the resultant analysis of variance table the F ratio for interactions, which includes those variances not accounted for by row and column effects, was computed as 0·04 ($F_{0\cdot95}$ (1, 6) = 5·99). Operator errors in counting therefore appear not to be significant.

APPLICABILITY OF THE MODEL

Consideration of the results of the experiment must be prefaced by some discussion of conformity to model. Generally, validity can be granted to the results of the analysis of variance model applied here if the following assumptions are satisfied: (1) that the populations dealt with are normal; (2) that effects are additive; (3) that the variances are homogeneous (Krumbein and Miller, 1953, p. 526).

A test for skewness involving calculation of the third moment of the distribution was carried out on a trial count of *Astrononion* sp. The resultant value for t = 2·61 is slightly beyond the 0·01 level of 2·58 (df = ∞). Departure from normality, while evidenced, seems not to be significant in this particular population, bearing in mind the demonstration by Cochran (1947) that departures from normality are not serious unless the distribution is highly skewed.

The question of non-additive effects has exercised those who have applied models similar to that used here to enumeration data. For example, Barnes and Marshall (1951, p. 237) in their study of the variability of plankton catches found it necessary to apply a logarithmic transformation to their raw data. In the present instance the necessity for making a transformation was tested by applying Tukey's test (Snedecor, 1956, p. 321) to the raw data for *Cassidulina neocarinata* Thalmann. The result of the test, F = 1·58 ($F_{0\cdot95}$ (1, 15) = 4·54) shows that the assumption of additivity is clearly allowable in the case analysed. Although Tukey's test has not been applied in every case, the raw data of other populations show little tendency to be distributed in Poisson fashion.

The third assumption, homogeneity of variance, cannot be tested in the present model as sampling was non-replicative.

RESULTS

A tabulation of census material for 15 populations together with the associated tests of significance is shown on Fig. 4.

Examination may first be made of census data for the populations of *Nonion maoricum* (Stache), *Gyroidina prominula* (Stache), *Cas-*

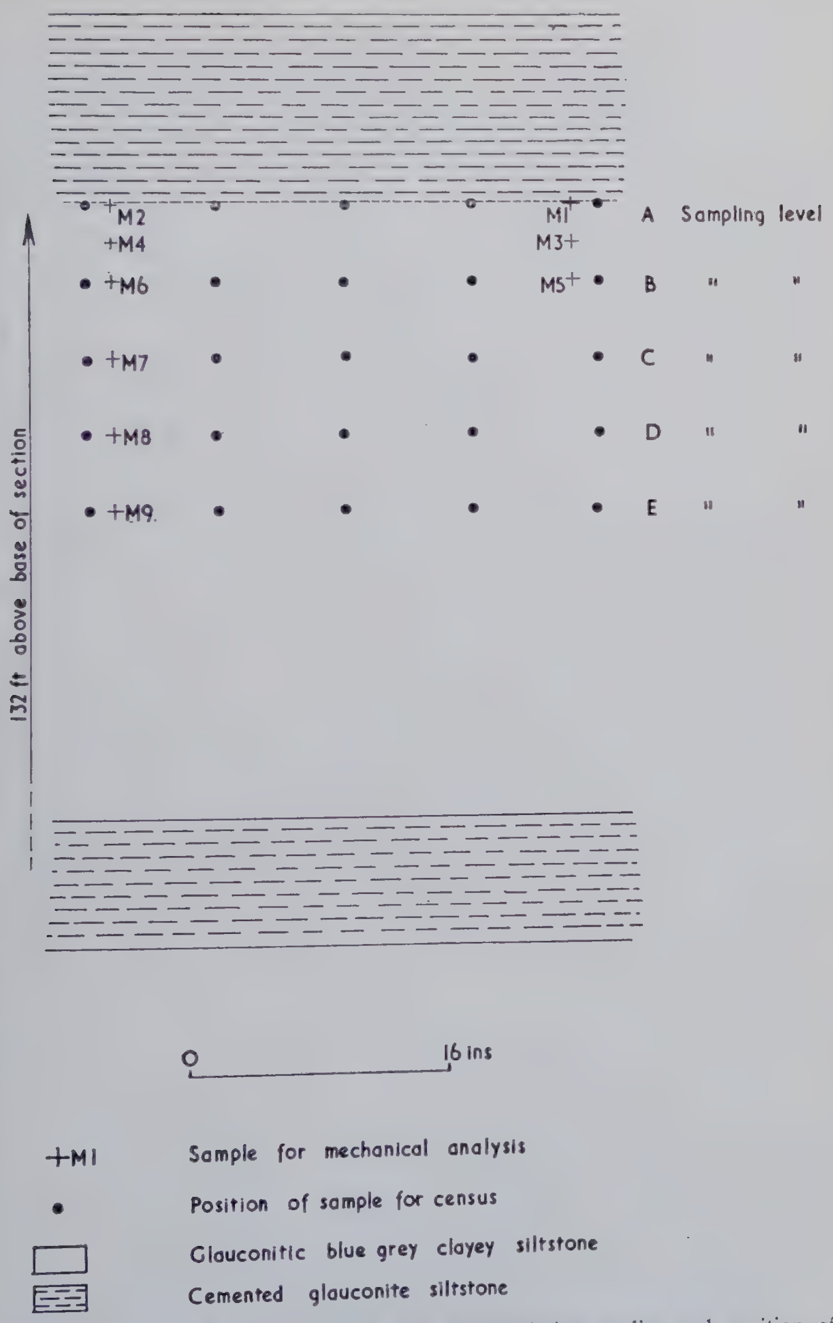

M1
M2
M3
M4
M5
M6
M7
M8
M9
A Sampling level
B " "
C " "
D " "
E " "
132 ft above base of section
0
16 ins
+M1 Sample for mechanical analysis
Position of sample for census
Glauconitic blue grey clayey siltstone
Cemented glauconite siltstone

FIG. 1.—Location of sampling grid used in population studies and position of samples used for mechanical analyses.

sidulina neocarinata Thalmann, *Robulus cultratus* Montfort, and *Globigerina* spp. The latter group includes a preponderance of *G. apertura* Cushman together with a smaller representation of *G. bulloides* d'Orbigny and *G. subcretacca* Lomnicki. These species had necessarily to be compounded into one census population because of the difficulty in identifying juvenile and broken specimens. Geographic variances in this group of species are not significant with the exception of the *Globigerina* population which slightly exceeds the 5% level. However, in every case row means exhibit heterogeneity. From this it may be inferred that sampling, for each of these species, was not from a common population, the source of heterogeneity lying in the stratigraphic dimension.

This situation is reversed when the tables for *Anomalinoides macraglabra* (Finlay) and *Cassidulina* sp. are considered. Here the source of heterogeneity lies in the geographic element of classification.

In a third group of species, samples appear to have been drawn from common populations. Neither geographic nor stratigraphic effects are significant in the grids for *Nonion* sp., *Astrononion* sp., *Notorotalia* aff. *serrata* Finlay, *Angulogerina* sp., *Bolivina anastomosa* Finlay, *Sphaeroidina bulloides* d'Orbigny, *Cibicides* sp., and *Cibicides* aff. *ihungia* Finlay.

INTERPRETATION

It is apparent from consideration of the experimental results that, for nearly half of the specific groups dealt with, heterogeneous populations exist within the area of the grid. It is therefore of high interest to probe into the possible causes of heterogeneity.

The distributional patterns exhibited by populations of fossil Foraminifera may be considered to be the result of the operation, either singly or interactively of two groups of dynamic influences—physical and biological. An essential concern is therefore to study the nature

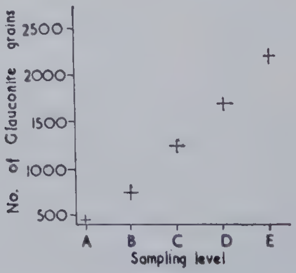


FIG. 2.—Plot of number of glauconite grains per unit volume against sampling level.

of the sedimentary universe delimited by the dimensions of the grid used in this experiment. Specific populations of Foraminifera drawn from this universe have shown statistically significant variation in frequency distribution; it is thus pertinent to observe whether samples taken from the same universe and analysed with reference to physical characters also exhibit heterogeneity.

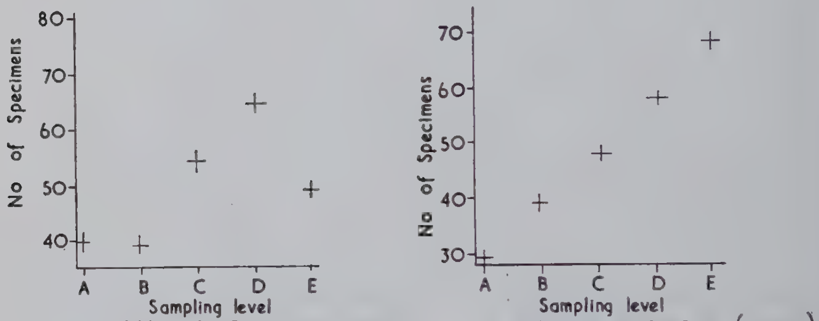
With a view to applying a simple analysis of variance model to grain size parameters, samples used for mechanical analysis were taken on the pattern shown in Fig. 1. A simple sampler taking a core of 20 mm diameter by 25 mm in length was used and to obtain a sufficient volume of sediment, two insertions were made at each locus. Standard techniques of pipette analysis (Krumbein and Pettijohn, 1938, p. 167) were used and values for the phi measures of Inman (1952) were derived from the plotted cumulative curves. Values for Md_φ, δ_φ, and α_φ for each of the three groups of samples together with the results of the associated tests of significance are given in Table 1. In no case is the hypothesis refuted at the 5% level that the means of each parameter for the three groups are equal. Within the limits of this analysis of variability of grain size parameters there seems no reason to suspect heterogeneity within the sedimentary universe.

TABLE 1.—Grain Size Parameters of Nine Analysed Samples Together With Associated Tests of Hypothesis.

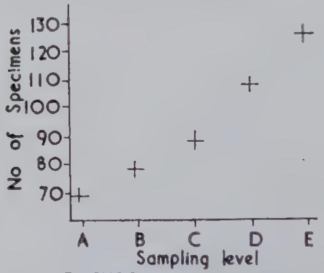
	Sample No.	Md_φ	δ_φ	α_φ
Group 1	M1 M3 M5	5·99 5·45 5·40	2·65 3·30 3·27	0·396 0·303 0·495
Group 2	M2 M4 M6	5·60 5·40 5·32	3·45 3·45 3·28	0·440 0·498 0·567
Group 3	M7 M8 M9	5·35 5·45 5·15	3·29 3·30 3·45	0·500 0·469 0·550

	Sum Squares	A. Md_φ d.f.	Mean Square	F.
Group Means	0·09	2	0·045	1·12
Within Groups	0·24	6	0·040	
Total	0·33	8		
		B. δ_φ		
Group Means	0·17	2	0·085	1·70
Within Groups	0·30	6	0·050	
Total	0·47	8		
$F_{0.95}(2, 6) = 5·14$				

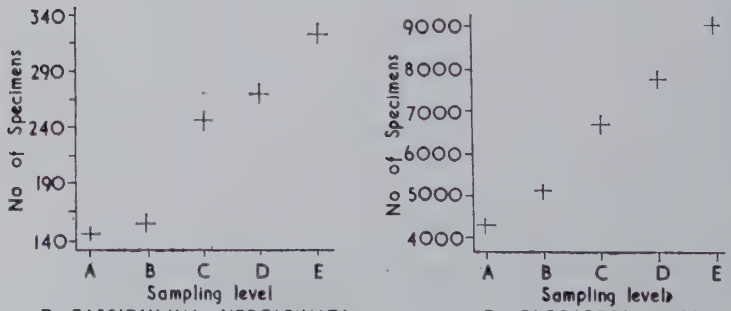
There is, however, another possibility to be considered. As sampling has been carried out upon a volumetric basis, it is apparent that differential rates of sedimentation during deposition of the universe could lead to stratigraphic effects of the type encountered in the



A ROBULUS CULTRATUS MONT B NONION MAORICUM (STACHE)



C. GYROIDINA PROMINULA (STACHE)



D CASSIDULINA NEOCARINATA THALMANN E GLOBIGERINA SPP

FIG. 3.—Plots of number of specimens against sampling levels for five populations which showed significant stratigraphic effects.

census data of some populations.

To obtain a measure of the rate of sedimentation during the deposition of the universe use was made of a glauconite index. This index is based upon the widely accepted belief that formation of this mineral is favoured by slow detrital influx (Cloud, 1955, p. 490) As the glauconite occurring in the sampling universe appears to be authigenic in terms of Light's criteria (1952, p. 74) and the possibility of non-masking refuted by the strong positive skewness of the sediment, it appears reasonable, as a first approximation, to consider the number of grains per unit volume as an index of rate of sedimentary influx. Figure 2 graphically illustrates the result of the analysis of five 0·40 cc samples taken throughout the stratigraphic extent of the grid. From the graph it is evident, accepting the adequacy of the index, that influx of detritus linearly increased during the deposition of the universe.

One possible effect of this increasing rate of sedimentation upon the distribution of foraminiferal populations may readily be deduced. If individuals of a specific population were in constant supply throughout the period of deposition, then a linear relation should obtain between numbers of tests and sampling levels. This hypothesis was tested in those populations which showed significant stratigraphic effects in variance analysis. Plots of numbers of specimens against sampling levels for these species are shown in Fig. 3. From inspection, a linear relation obtains for the populations of *Nonion maoricum* (Stache), *Gyroidina prominula* (Stache), *Globigerina* spp. and possibly for *Cassidulina neocarinata* Thalmann. No such relation is shown in the plot for *Robulus cultratus* Montfort.

It may be remarked here that the argument developed concerning the effect of rate of sedimentation upon censuses of foraminiferal populations receives substantial support from workers in the field of modern ecology. Walton (1955, p. 998) mentions that "In areas of little or no sedimentation, large populations of empty shells accumulate. Areas undergoing rapid sedimentation, on the other hand, might have a relatively small population of empty shells even though both areas have comparable living populations." Smith (1955, p. 151) and Phleger (1956, p. 110) concur with this view. Nevertheless it is manifest that the sedimentation hypothesis cannot adequately account for all observed cases of stratigraphic heterogeneity and certainly not for the two examples of geographic heterogeneity. As considered previously, dynamics of specific populations no doubt interact with sedimentary influences in producing the final form of distribution of fossil populations. It is a matter for future research to analyse the nature of this interaction and to assess the effect of diagenetic factors.

ROBULUS CULTRATUS MONT.

4	8	9	10	9
3	10	8	12	6
13	11	14	7	9
13	11	18	13	19
13	15	11	8	11

F Row = 4.23*
F Col = 0.56

NONION MAORICUM (STACHE)

8	6	9	3	3
2	11	13	7	6
13	10	6	10	9
11	10	10	15	12
19	13	10	9	18

F Row = 3.53*
F Col = 0.15

NONION SP

2	16	6	9	4
8	2	13	7	13
9	6	8	14	15
7	6	5	10	12
11	10	6	6	9

F Row = 0.35
F Col = 0.44

ASTRONONION SP

3	4	9	6	11
7	4	4	7	5
7	5	5	7	5
3	7	8	7	6
6	11	4	5	4

F Row = 0.07
F Col = 0.16

NOTOROTALIA aff SERRATA FIN

20	24	43	26	11
11	27	31	29	25
31	16	18	17	18
21	25	22	18	20
21	23	24	13	25

F Row = 0.45
F Col = 0.90

ANGULOGERINA SP

12	32	45	40	52
15	12	60	42	46
43	37	61	65	60
30	39	31	46	36
49	41	53	32	45

F Row = 0.28
F Col = 1.01

BOLIVINA ANASTOMOSA FIN

7	15	18	17	8
4	8	14	13	13
12	8	22	19	20
17	15	15	16	13
23	15	13	12	15

F Row = 1.34
F Col = 0.75

GYROIDINA PROMINULA (STACHE)

7	17	16	11	18
14	4	15	20	25
15	15	15	23	20
15	27	17	30	20
17	24	30	22	33

F Row = 3.90*
F Col = 2.45

SPHAEROICLINA BULLOIDES D'ORB

8	3	10	10	8
5	6	7	7	9
11	18	10	6	9
8	11	6	4	11
6	11	15	8	3

F Row = 0.85
F Col = 0.63

CASSIDULINA NEOCARINATA THAL

11	29	48	27	31
18	23	55	42	16
45	51	44	43	66
55	61	44	58	52
62	54	75	54	79

F Row = 8.31**
F Col = 1.13

CASSIDULINA SP

4	9	8	11	14
8	6	10	11	10
11	5	7	9	12
10	4	4	9	10
9	2	5	4	6

F Row = 2.52
F Col = 3.54*

ANOMALINOIDES MACRAGLABRA (FIN)

9	8	19	15	25
17	8	14	14	14
15	13	27	17	24
25	15	15	20	18
23	14	19	21	21

F Row = 2.12
F Col = 3.13*

CIBICICLES SP

41	41	54	32	38
40	39	53	47	47
60	55	44	31	53
35	50	41	51	48
54	51	59	33	41

F Row = 0.53
F Col = 1.15

CIBICICLES aff IHUNGIA FIN

20	17	24	13	20
18	16	28	22	16
36	25	19	17	23
27	18	18	24	18
25	27	30	22	23

F Row = 1.63
F Col = 1.33

GLOBIGERINA SPP

306	683	1419	939	991
803	795	1433	1247	845
1195	1182	1439	1236	1672
1531	1612	1580	1556	1457
1738	1725	2188	1366	2005

F Row = 13.54**
F Col = 3.51*

FIG. 4.—Census grids and tests of significance for the populations studied. *indicates significance at 5% level; ** indicates significance at 1% level.

Note: *Sphaeroclina* should read *Sphaeroidina, Cibicicles* should read *Cibicides.*

CONCLUSION

The prime object of this experiment was to investigate the nature of the distribution of individual members of a faunule within one lithologic unit. To take a single sample from a bed and consider it as representing adequately the numerical strength of the faunule seemingly involves the assumption that members are uniformly distributed throughout the unit. The results of this study do not bear out this assumption. Experimentally it was found that while, for some species, samples were drawn from common populations, there were other taxonomic groups for which sampling was not from one population. It seems, therefore, that to take a single sample from a bed is merely to measure the result of the interaction of physical and biological processes at that particular locus in the bed or sampling interval. One sample clearly cannot be made the basis of a generalization designed to cover the whole of the sampling interval.

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GEOLOGY OF MOTUIHE ISLAND, WAITEMATA HARBOUR

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Summary

Waitemata Formation strata of probable Otaian age, unconformably overlie a highly irregular, unweathered surface cut in rocks of Mesozoic age. A tuffaceous sandstone within the former is correlated with the Parnell Grit horizon. It contains large blocks of Waitemata sandstoie and mudstone.

The majority of dips are considered to be the result of compaction rather than tectonic movement.

The ground-water reservoir consists of an irregularly shaped fresh-water lens resting on salt water. A few drillholes that originally supplied fresh water have become salty. Others may do so unless pump intakes are kept at or above mean sea-level.

INTRODUCTION

Motuihe is an irregularly shaped island, roughly 30 to 80 chains wide (Fig. 1). It lies to the east of Rangitoto Island near the entrance to Waitemata Harbour. Supplies of fresh water are required, and, as several drillholes have yielded salty water, a geological survey of the island was requested.

Outcrops are mainly confined to the coast, and were examined during a visit of one and a half days.

GEOLOGY

Apart from the isthmus of sand which joins the small western portion to the main part of the island, Motuihe is composed of Tertiary rocks (Waitemata Formation) overlying Mesozoic greywacke (Fig. 1). Although the island is 205 ft above mean sea-level, except for a grass-covered raised beach at a little more than 5 ft above mean sea-level, no terrace remnants exist.

Stratigraphy

GREYWACKE

The greywacke is a hard, blue, massive, jointed, medium-to-coarse sandstone of Mesozoic age.

N.Z. Geol. Geophys. 1 : 485-9.

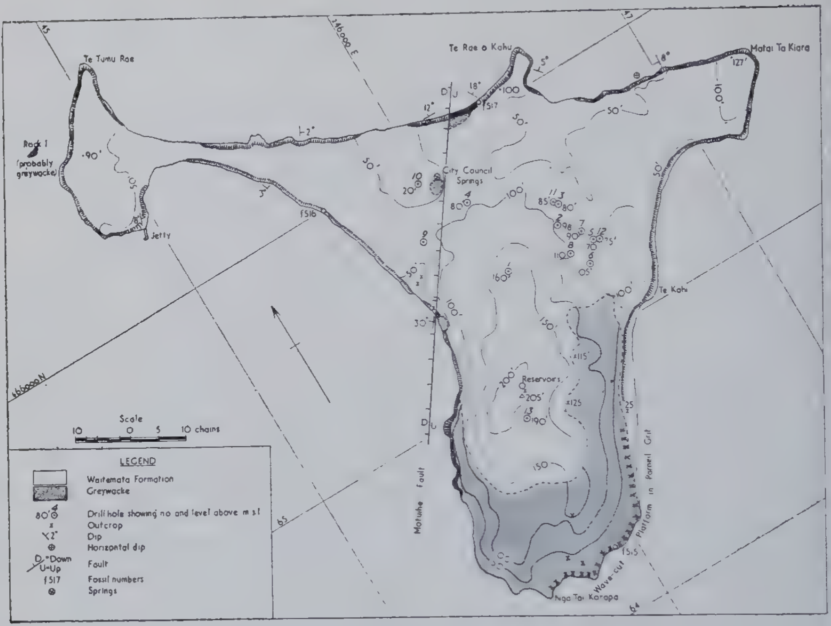

FIG. 1.—Geological map of Motuihe Island, Waitemata Harbour.

WAITEMATA FORMATION

The Waitemata Formation consists of well consolidated, interbedded marine sands and clays. Outcrops and drill logs (see Table 1) show an irregularly distributed basal conglomerate. Graded bedding and carbonaceous flakes are common, whereas ripple marks and small-scale current bedding are rare. Interbedded in the normal Waitemata facies is a tuffaceous, dark grey, medium sandstone, 10 to 60 ft thick, which may be correlated with the Parnell Grit. Confined to this horizon are thin beds of angular fragments of Waitemata mudstone and sandstone, usually concentrated at the base, and numerous large boulders of the same material, up to 10 ft in diameter. The bedding within some of the boulders has been contorted, and small dykes of Parnell Grit commonly intrude along the fold axes of the contortions.

The contact of the Parnell Grit with the overlying Waitemata beds is gradational, whereas its lower contact is sharp and irregular.

Immediately west of Motuihe Fault on the west coast (Fig. 1), a well cemented, greywacke conglomerate exists locally at the base of the Parnell Grit. Its top consists of rounded, coarse, and medium grained greywacke pebbles, commonly 1½ to 2 inches in diameter, embedded in a sandstone matrix. It grades downwards, within 10 ft, to a coarse angular conglomerate with pebbles commonly 4 inches in size embedded in a shell limestone matrix which contains large oyster fragments.

Boulders up to 18 in. are scattered throughout.

Mr N. de B. Hornibrook, of the New Zealand Geological Survey, has reported on three foraminiferal samples. Sample N42/516 from 6 ft above the Parnell Grit was unfossiliferous. Sample N42/515 from immediately below or within the Parnell Grit contained common Globigerinas:

Globoquadrina subdehiscens Finlay
Globigerina apertura Cushman
G. bulloides d'Orb.

and lacked *Elphidium, Notorotalia,* and other forms that inhabit shallow water. Its age is assessed as Pareora.

Sample N42/517, 80 ft below the Parnell Grit and 4 ft above greywacke, contained:

Sigmoilopsis cf. *celata* (Costa)
Stilostomella consobrina (d'Orb.)
Bolivina n.sp. (of Mahoenui)
B. n.sp. (of Clifden)
B. beyrichi Reuss
B. anastomosa Finlay
B. subcompacta Finlay
Loxostomoum n.sp. aff. *truncatum* Finlay
Rectobolivina maoriella Finlay
Virgulopsis sp.
Uvigerina aff. *canariensis* d'Orb.
Chilostomelloides sp.
Nonion aff. *pompilioides* Fitchell and Moll)
Pullenia bulloides (d'Orb.)
Globortalia aff. *scitula* (Brady)
Globigerina dissimilis Cushman & Bermudez
Globoquadrina subdehiscens Finlay

Despite abundant Globigerinas in N42/517, the upper Pareora and Southland species, *Globorotalia miozea,* is absent, and a lower Pareora age, probably Otaian, seems most likely.

GREYWACKE-WAITEMATA CONTACT

The contact between the Waitemata Formation and the underlying greywacke is highly irregular. Most of the south-east coast line between the headlands of Te Kahi and Nga-Tai-Korapa consists of greywacke hills, up to 150 ft high, rising steeply from a wave-cut platform carved in Parnell Grit. The contact between the two is exposed about 12 chains east of Point Nga-Tai-Korapa. Although the Parnell Grit is almost horizontal, the contact with the greywacke is nearly vertical and very irregular. The greywacke is fresh, and blocks dislodged from joints have been replaced by an infilling of Parnell Grit.

Structure

The Motuihe Fault (Fig. 1) shows on air photographs as a slight depression, and could well have given rise to the springs which provide the City Council water supply of the island. Its plane has not been exposed.

Dips are generally low and of no preferred direction. The 30° dip near the south-west end of the fault may be due partly to faulting and partly to the original slope of the breccia (a talus slope?) in which it was recorded.

Dips are apparently away from basement highs, as is well shown in the central north-east coast. Farther west, the beds may well dip away from another basement high represented by Rock Island (Fig. 1). As there is no constant structural trend shown, most of the dips may be due to compaction.

Ground-water

Table 1 gives all the available drillhole information. Holes, recorded as having no water, encountered greywacke at 30 ft or more above sea-level, and, as the water table has been recorded above this level in only one hole, the greywacke of the island is nowhere yielding sufficient water. This is not surprising, as most small supplies that may be obtained from greywacke elsewhere come from the weathered zone which is absent on Motuihe.

The Waitemata beds are normally fairly impermeable and yield large supplies only when the beds are fractured.

The ground-water body probably consists of a fresh-water lens of a highly irregular shape. Many of the drillholes have penetrated below sea-level and yielded fresh-water on testing. Few of these have been constantly used, but several that have been, have become contaminated with sea-water. The simplest method of safeguarding supplies is to keep all pump intakes at or above mean sea-level.

TABLE 1.—Details of Drillholes.

No.	Driller's log	Thick-ness (ft)	Level of water table above sea-level	Yield (gal. per hr)	Remarks
1	Clay and sandstone	65	—	Nil	
	Rubble rock	30			
	Hard fractured rock	34			
	Hard rock	34			
2	Clay and sandstone	60	27	720*	
	Volcanic ash	25			
3	Clay	40	14	720*	
	Volcanic ash	49			
	Fissure	3			
4	Clay	41	44	720*	
	Volcanic ash	41			
	Gravel	—			
5	Clay	28	5	720*	
	Volcanic ash	56			
	Mudstone	56			
	Broken gravel	—			
6	140 ft deep	—	—	300	
7	160 ft deep, rock at bottom	—	—	—	Pumped salt water
8	140 ft deep, rock at 80 ft	—	—	Nil	
9	————————				Turned salty
10	55 ft deep	—	—	—	Turned salty
11	132 ft deep, rock at base	—	—	100	
12	White clay	28	—	170	
	Hard sandstone	55			
	Greywacke	—			
13	120 ft deep, rock at base	—	—	Nil	

*These holes were tested at this rate for 12 to 18 hours, but no measurements were made of the drawdown; nor is there any record of the pump level during the test.

THE STRUCTURAL POSITION OF THE OPAU GREYWACKES, HAWKE'S BAY

By J. T. KINGMA, New Zealand Geological Survey, Department of Scientific and Industrial Research, Lower Hutt.

(Received for publication, 27 May 1958)

Summary

A structure in the young Tertiaries of the Patoka district, northern Hawke's Bay, is anomalous when the area is compared topographically with districts further north and south. A faulted body consisting of greywackes of probable Jurassic age, has pushed the Tertiary and its lower Pleistocene cover up, and initiated the local anomalous topography. The action started in Nukumaruan time. The movement had a mild southern component causing disturbance in the area immediately north of the Opau greywackes.

PREVIOUS GEOLOGICAL WORK

Hill (1899) described the Puketitiri area and summed up his findings in a section between Napier and the Kaweka Range. The Opau greywackes were not known to Hill. The Maniaroa limestones were considered to be younger than those at Puketitiri and even younger than the deposits at and east of Patoka settlement, now known to be Nukumaruan in age. No faults were shown. The limestones in the Puketitiri district, having been found to contain large numbers of *Ostrea ingens* Zitt., were assigned to the upper Miocene.

TOPOGRAPHIC SETTING

The area under examination is located in the western third of N124 (N.Z.M.S. 1) between the farm settlements of Patoka and Puketitiri (Figs 1, 2). The area rises to just over 2,600 ft in the Te Waka and to over 2,300 ft in its southern extension, the Maniaroa Range, from where the country falls southward towards Hawkeston settlement and the Tutaekuri River. The Waipuna Stream, marking the boundary between the Te Waka and Maniaroa ranges, is also the boundary between two different types of topography. The area north of the Waipuna is one of outstanding relief strongly characterized by active erosion. The district south of the Waipuna has also a marked relief but erosion is much less vigorous.

Whereas the general dip of the strata north and south of the Opau region is towards the east-south-east (Fig. 1) the regional dip in the Opau area markedly changes to south, and a highly disturbed and eroding country lies between the Opau area and the Te Waka

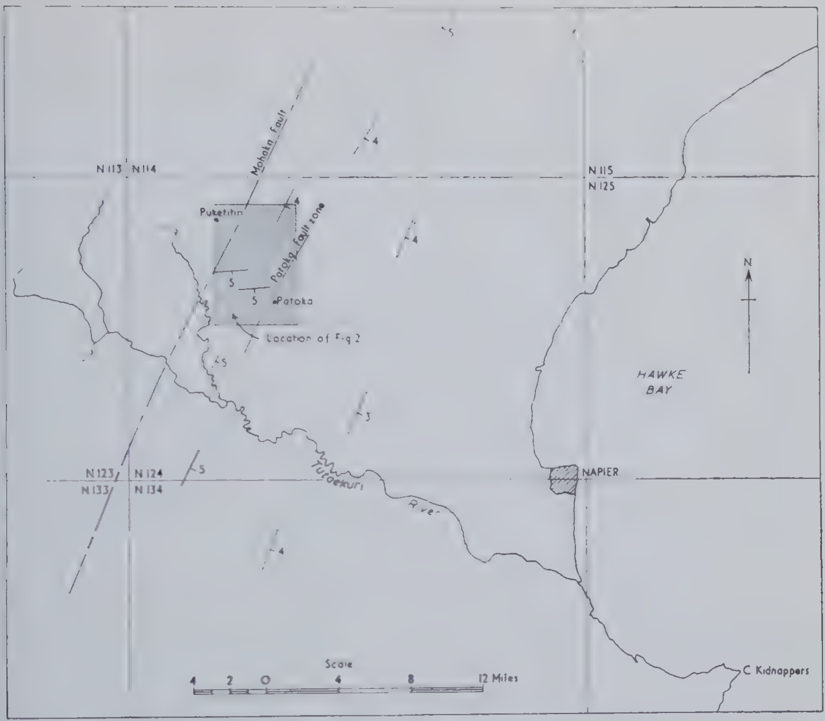

FIG. 1.—Locality map showing main faults, topographical features, and regional dips in the northern Hawke's Bay strata.

Range farther north. East of the Opau area the strata dip east-south-east. The anomalous topography of the Opau area was investigated in 1957 and a possible tectonic explanation of this rather extraordinary feature is advanced.

STRATIGRAPHY

The lithology and age of beds in the Opau district is shown in the following stratigraphical column.

N.Z. Series and Stages	Lithology	European equivalent
Recent	Gravels, sands, and muds in valley floors	Holocene
Nukumaruan	Gravels, massive fossiliferous sandstones with occasional limestone bands, massive siltstone	Lower Pleistocene
Waitotaran	Pebbly limestone overlying silty sandstones	Upper Pliocene
	Unconformity	
Jurassic	Alternating sandstones and siltstones, cherts (greywacke undermass)	Jurassic

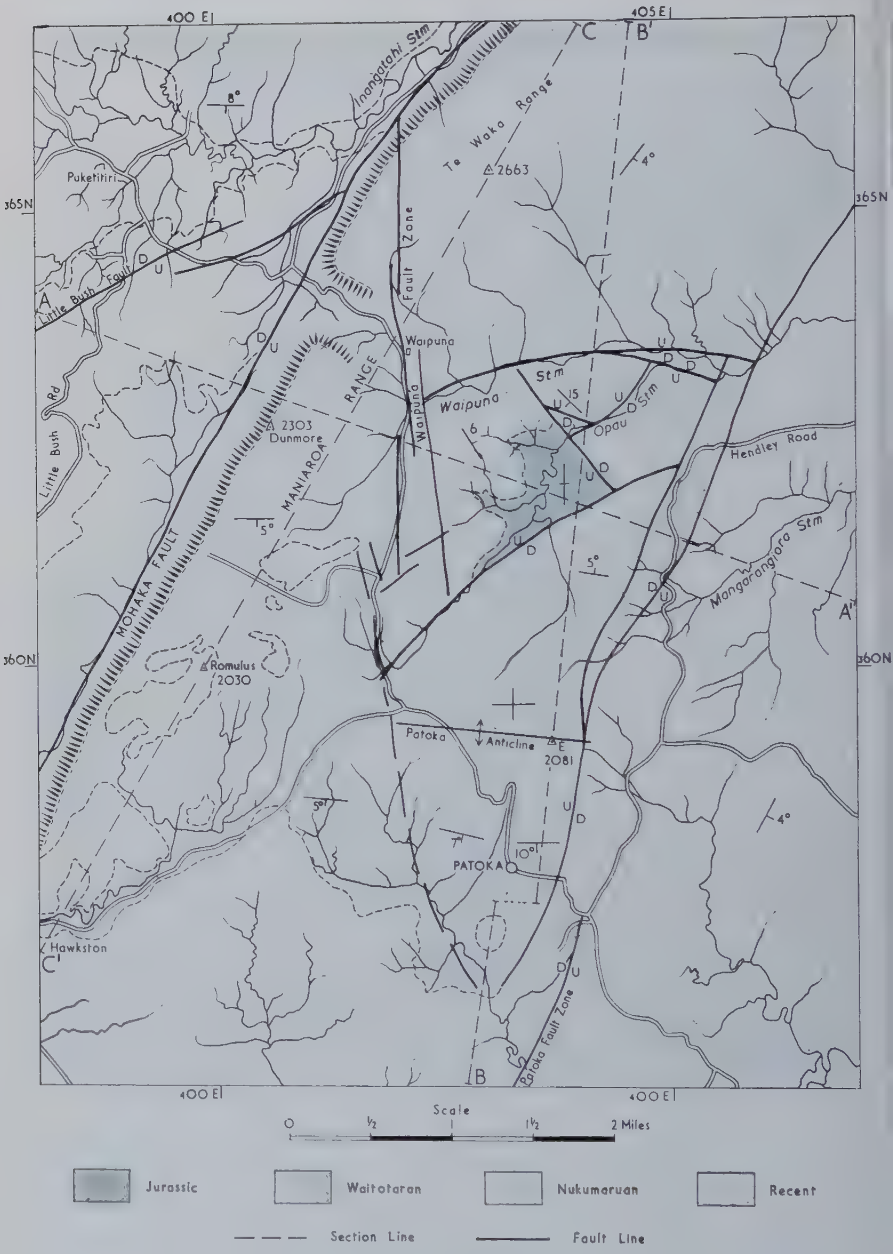

Fig. 2.—Geological map of the Opau area.

Greywacke Undermass.

Greywacke rocks, outcropping in an area of approximately 1½ square miles are cut by the Opau Stream, exposing north-striking beds; mainly vertical these beds show magnificent graded bedding in sandstone-siltstone cycles approximately 1 ft in thickness. Occasional large blocks of red rock are to be found in the Opau Stream; a sample of this rock was identified by Dr J. J. Reed (pers. comm.) as calcified radiolarian jasper. The rock is undoubtedly from the greywacke sequence, but was not found in situ.

The sandstone beds clearly show microlayering in the sense described by Kingma in 1958 and termed Makara Facies (Kingma, 1958a). The graded sequence closely resembles that of the Wakarara Range (Kingma, 1958b) and is more or less in the extension of the strike observed in the Wakarara Range. The finest grade has been investigated on its microfloral content (sample L.940). The following identifications and discussion is presented by Dr R. A. Couper.

The sample yielded only a poor flora of some 10 species of spores and pollen grains. The following were identified:

Podocarpidites major Couper
Podocarpidites sp.
Classopollis torosus (Reissinger) Couper
Araucariacites australis Cookson
Monosulcites minimus Cookson
Pteruchipollenites cf. *thomasii* Couper
Cyathidites australis Couper
C. minor Couper
Osmundacidites wellmanii Couper
Lycopodiumsporites clavatoides Couper

Specimens of as yet unidentified fossil microplankton (Dinoflagellates and Hystrichosphaerids) are also present.

AGE

Classopollis torosus (Lias-Lower Cretaceous) and *Pteruchipollenites thomasii* (?Jurassic) are characteristic of Jurassic floras in New Zealand and elsewhere. *Osmundacidites wellmanii*, *Araucariacites australis*, *Cyathidites australis*, *C. minor*, and *Podocarpidites major* are common elements in New Zealand Jurassic floras but extend into the Cretaceous and younger beds.

The species present favour a Jurassic age but the possibility of a lower Cretaceous age cannot be ruled out until more work is done on New Zealand Mesozoic spore and pollen floras. The absence of the coniferous pollen species *Dacrydiumites mawsonii*, *Microcachryidites antarcticus*, and *Dacrydium microsaccatum* which characterize New Zealand upper Cretaceous floras is evidence of a pre-upper Cretaceous age, particularly as the sample is dominated by other coniferous species

(*Classopollis torosus, Araucariacites australis*). Also the absence of angiospermous grains is further evidence of a pre-upper Cretaceous age.

Waitotaran Strata

Waitotaran strata are exposed over a large area but neither the lowest beds of this stage nor the preceding Opoitian has been observed. The stage, as elsewhere in Hawke's Bay, has developed into two facies, i.e., a lower Waitotaran sandstone covered by an upper Waitotaran limestone. The sandstone facies consists of a rather monotonous brown-grey, medium grained, calcareous sandstone without obvious macrofossils. In some places a coarsening towards the overlying limestone is noticeable.

The limestone facies consists of a hard, well cemented coquina with varying amounts of greywacke pebbles. The pebbles vary in size from place to place, and an excellent gradation in pebble size may be observed on the western side of the Maniaroa Range. This limestone forms a magnificent escarpment where it is cut by the Mohaka Fault and, from approximately 200 ft at Hawkeston, the thickness decreases northward to about 20 ft at the culmination of the Maniaroa Range, i.e., at Trig. Dunmore, 2,303 ft. Immediately north of the Waipuna fault zone, the thickness increases again and is about 200 ft throughout the Te Waka Range. The above mentioned thinning to Trig. Dunmore is accompanied by a decrease in pebble size from 1 to 3 in. diameter at Hawkeston to less than ½ in. at Trig. Dunmore. The base of the limestone close to the Opau greywackes is packed with angular blocks of greywacke up to 1 ft in diameter, indicating that the greywacke was exposed to wave action at the time of deposition of the limestones. No greywacke blocks occur higher in the limestone at these places.

The standstone contains a Waitotaran microfauna (F7054, 8852) in the Miroroa area, that is, south of the Patoka-Puketitiri area. The limestone there contains large numbers of *Ostrea ingens* Zitt. and *Phialopecten triphooki* (Zitt.); the same fossils are known from personal observation from the Te Waka Range in the northernmost part of the district, and *Ostrea ingens* Zitt. was observed by Hill (1899) in the Puketitiri limestones. In the Patoka-Puketitiri area the Waitotaran index fossil *Maoricardium spatiosum* (Hutt.) (GS 7060) is well represented in the limestone and there is no reason to doubt that the Waitotaran stage in he Patoka-Puketitiri area follows the same sedimentological pattern as elsewhere in Hawke's Bay, so that the top of the limestone may also be accepted here as the top of the Tertiary.

Nukumaruan Strata

Nukumaruan strata are known from the areas north and south of the Patoka area. GS 4565 from the Te Pohue area, 6 miles north of Patoka, yielded *Chlamys delicatula* (Hutt.) and *Phialopecten triphooki* (Zitt.) indicating a lower Nukumaruan age. McKay in 1887 (GS 703) collected a large number of Mollusca from the Te Waka Range at Te Pohue and correlated these fossiliferous deposits with the limestones at Napier and at Te Aute. These beds overlie limestones which from personal observation have been found to contain *Ostrea ingens* Zitt. and *Phialopecten triphooki* (Zitt.). The occurrence together of these two species is indicative of the Waitotaran stage, and their absence in collection GS 703 and in the beds yielding it (pers. observ.), strongly suggest that the age of these beds is Nukumaruan. The lower Napier limestone, which is lower Nukumaruan in age on both micro and macrofaunal evidence (F.9644; GS 5405, 5423), can therefore be correlated with the beds that yielded collection GS 703, and is younger than the Te Aute limestones.

The sequence south of the Patoka district consists of an upper Waitotaran limestone with lower Nukumaruan silty mudstones. These silty mudstones are the basal beds of a great sequence of Nukumaruan strata containing a wide variety of lithologies ranging from siltstone to conglomerates. This Nukumaruan sequence may be observed to the east of Patoka, where a vast expanse of Nukumaruan rocks may be traced into northern, central, and southern Hawke's Bay.

There seems to be no doubt that everywhere in Hawke's Bay the Tertiary-Quaternary boundary coincides with the top of the Waitotaran limestone. The sequence in the Patoka district is unlikely to be different and, although not entirely supportable by paleontological data, all rocks overlying the Waitotaran limestone are here placed in the Nukumaruan.

The lithology in this stage ranges from the blue grey medium grained silty sandstones to conglomerates. Brown, coarse sandstones with sandy limestone bands have been found on the eastern side of Potters Road, where the limestone bands are occasionally overcrowded with *Zethalia* cf. *coronata* Marw. (GS 7066). Mrs G. H. Scott (pers. comm.) informed the writer that the ornamentation of this species is closer to the *Z. coronata* than to the later *Z. zealandica* and consequently might be evidence for an older age. Fossils were collected from very fossiliferous silty sandstones (GS 7065) situated at approximately the same horizon as GS 7066 and containing the following species:

Patro (*Prismatro*) *undata* (Hutt.)
Ostrea sinuata Lk
Chlamys cf. *gemmulata* (Reeve)
Venericardia purpurata (Desh)
Pteromyrtea dispar (Hutt.)

Scalpomactra cf. *scalpellum* (Reeve)
Marama murdochi Marw.
Maoricardium spatiosum (Hutt.)
Zeacolpus sp. (worn)
Maoricrypta radiata (Hutt.)
Turrid sp. indet.
Neothyris sp.
Balanus? *tubulatus* Withers

The age of this sample is determined by the occurrence of *Maoricardium spatiosum* (Hutt.) which bring the age of this sample into the Waitotaran. As this species is, however, only represented by worn fragments which are bored on the outside as well as on the inside of the valve, the author considers that these fragments are derived from earlier Waitotaran strata where this particular *Maoricardium* is quite common. As the top of this stage is nowhere preserved, the thickness of the Nukumaruan strata is not known, but a minimum thickness of at least 500 ft may be expected.

The small Nukumaruan erosion remnants on the south-dipping Maniaroa dip-slope consist of blue grey siltstones immediately overlying the Waitotaran limestone. A 6 ft conglomeratic limestone band forms the top of Trig. Romulus (2,030 ft) and may be traced southward into the Nukumaruan sequence where it grades into one of the lower Nukumaruan gravel beds. The Waitoaran-Nukumaruan boundary is abrupt, but wherever it has been observed is conformable. The Opau greywackes do not seem to have influenced the Nukumaruan lithology and they may not have been exposed during that time. In the Puketitiri district, vast amounts of gravel and near-shore beds with plant remains occur in the higher parts of the stage, forming excellent exposures along the Little Bush Road.

Recent Deposits

Recent river debris, lower-level valley filling, and a few very low terraces have been formed from the huge quantities of erosion products resulting from the high relief in this area. There is a surprising absence of high terraces, indicating that the deformation of the area started at a late date and that transport of eroded material away from the area was rapid. Pumice from the central part of the North Island is incorporated in the recent deposits but is nowhere of any magnitude. Along the Mohaka fault, where it crosses the Patoka-Puketitiri Road, pumice deposits with bands of gravel are being quarried for road metal. Evidently the pumice beds had a much wider distribution north and south along the fault.

Slumping from the high limestone escarpment has taken place along the Mohaka Fault, in some instance blocking the streams as has happened in historical time in the Inangatahi Stream, approximately 4 miles up the Potters Road from the turnoff. Many very large blocks (10 ft diameter) of Waitotaran limestone are scattered over the escarpment slope of the Maniaroa Range on the upthrown side of the Mohaka fault, indicating that the limestone escarpment is breaking up rather rapidly.

STRUCTRURE

Main Fault Systems

The main fault systems of the district are the Mohaka and Patoka fault zones. The Mohaka fault zone continues over very large distances farther north and south. Northward the fault zone follows the valley of the Inangatahi Stream and farther north the course of the large Mohaka River (Kingma, 1955). Southward the fault may be followed as far as the Wakarara district (Kingma, 1958b) from where it joins the Ruahine and Wellington faults. In the Patoka-Puketitiri area the Mohaka fault zone is represented only by a single fault. Vertical displacement is obvious all along the fault and is of the order of 700 ft in the Puketitiri area. No evidence of transcurrent movement has been observed in the field nor on aerial photographs.

The Patoka fault zone starts 6 miles south of Patoka and dies out north of Hendley settlement in the north-eastern part of the district. The throw along this fault is to the east and reaches a maximum of 400 ft about 2 miles north of Patoka. No evidence for transcurrent movement has been found.

Minor Fault Systems

The area between the Patoka and Puketitiri fault system is intersected by a great number of faults and fractures usually without much displacement. The fault following the Waipuna Stream, immediately north of the Opau greywackes, starts in the west as a minor fracture but displacement becomes increasingly larger eastward with throw to the north. Slumping of large limestone blocks and erosion in general very greatly complicate tectonic interpretation north of the Opau area. The Little Bush Fault along the southern side of the Pukeitiri Depression has a very clear fault trace, strongly suggesting recent movement along this fault; displacement along this fault caused the Puketitiri Depression.

Folding

Folding has been observed only south of the Opau greywackes where an anticlinal structure shows up in the Waitotaran limestones. This anticline—the Patoka Anticline—has a northern flank dipping at about 5° to the north and a slightly steeper southern flank which is

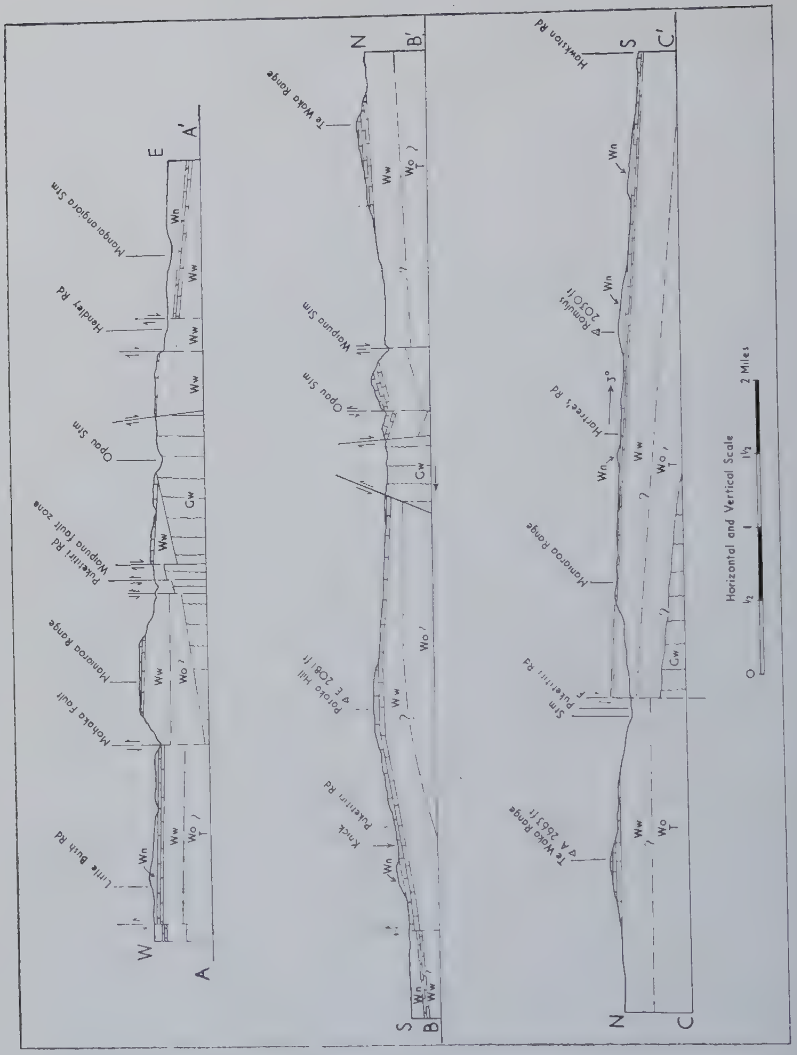

FIG. 3.—Cross-sections through the Opau area.

rather fractured, but in which a general dip of 10° south may be observed. No other folded strata are known.

HISTORY OF TECTONIC MOVEMENT

The Tertiary strata provide lithological evidence for tracing the movements that affected the Opau greywackes from the lower Waitotaran onward. Blocks obviously derived from the Opau greywackes occur in the very base of the upper Waitotaran limestone but not higher in those beds. Not enough is left of the Nukumaruan sediments surrounding the Opau greywackes to provide conclusive evidence concerning the history of the Opau greywacke during the Nukumaruan; the Nukumaruan outliers on the Maniaroa Range seem to be unaffected by the Opau greywackes as far as their lithology is concerned. The Opau greywackes were thus definitely within reach of eroding forces for a short period in the upper Waitotaran. Whereas the Waitotaran strata west and east of the Mohaka Fault are similar, the Nukumaruan lithology shows considerable differences, and the lithology west of the fault is totally different from that east of the fault. It may be deduced from this that vertical movement along the fault commenced in the lowermost Nukumaruan initiating the continuous uplift of the Opau area.

The isolated occurrence of the Opau greywackes which are surrounded by a great thickness of young rocks, suggests that the Opau greywacke body is another splinter of the North Island Geanticline that became separated from the main greywacke body during the Kaikoura diastrophism. The faulted nature of the north-eastern and south-eastern margins and the sedimentary contact between greywacke and Tertiary on the western side probably indicates that the Opau greywacke body represents the corner of a tilted block. This point pierced the Tertiary cover during the upward movement of the block. A mild southerly component in this movement displaced the block southward, causing the warping in the Patoka Anticline and the tilting of the Maniaroa dip-slope (Fig. 3). The southward movement also caused rupturing on the northern side of the gryewackes, which resulted in the Tertiary strata there being broken up into small and large blocks and initiated heavy erosion along the fractures.

ACKNOWLEDGEMENTS

The author wishes to express his indebtness to Messrs W. H. Hartree and G. Holt, both of Puketitiri for their help in the field. Mr Hartree was the first to bring the Opau greywackes to the author's notice and in 1952 showed him a sample of the rock. He also drew the author's attention to one of the Nukumaruan outliers on the Maniaroa dip-slope. Thanks are also due to the author's former Utrecht University colleague, Dr J. van der Sijp, Chief Geologist of the Shell-d'Arcy & Todd Oil Services Ltd., at present residing in New Zealand, with whom this paper was discussed and who made some valuable comments as to the possible structure of the Opau greywackes.

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PLEISTOCENE AND RECENT STUDIES OF WAITEMATA HARBOUR

PART 1—THE MAIN CHANNEL

By E. J. SEARLE, University of Auckland.

(Received for publication, 24 March 1958)

Summary

Some features of the bed of Waitemata Harbour are described and four cross profiles of the main stream are presented. The profiles afford evidence of an interval of stillstand during the Last Glaciation or earlier at an elevation approximately 30 feet below modern sea-level.

In an earlier paper, Searle (1956) discussed the importance of Pleistocene and Recent events in the development of the topography of the Auckland isthmus, following the lead of Brothers (1954) who integrated the various surface levels in the Auckland district with eustatic changes in sea-level during the Pleistocene and so established a local chronology for the area. It is proposed in this and later studies to consider features of Waitemata Harbour and its coastal areas and to examine their relevance to the Pleistocene history as established for the adjacent land areas.

Extensive engineering works and other projects in and about the harbour in recent years have greatly increased knowledge of the sub-surface geology of the district. In particular, much information has been forthcoming from intensive exploratory drilling carried out in connection with the following works and to the officers of the various authorities involved the writer is grateful for charts, bore records, and other data which they readily made available to him. The Auckland Harbour Board has surveyed the harbour floor in the vicinity of the port of Auckland, as well as in the upper harbour, in anticipation of expanding port facilities. The Auckland Metropolitan Drainage Board has drilled extensively in the coastal areas east of the port and on the isthmus. The Ministry of Works has sunk a large number of bores in the Shoal Bay and Hobson Bay areas, and Messrs Freeman, Fox, and Partners, contractors on the harbour bridge, have made a detailed survey along the line of the bridge.

Waitemata Harbour has long been recognized as a drowned river valley of the bottleneck type that shows in its deeply embayed coastline and wide marginal estuaries all the features characteristic of recent submergence. The locality map (Fig. 1) shows two clearly distinct reaches to the harbour proper. A relatively narrow section about 2 miles wide extends westward from the entrance for about 5 miles, having on its northern shore the shallow splayed-out embayments of Shoal Bay, and on the southern those of Hobson and

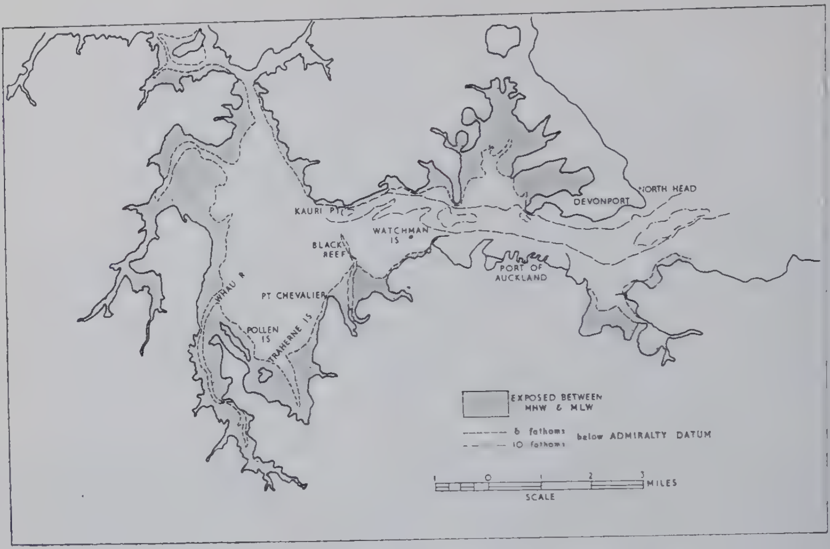

Fig. 1.—Locality map: Waitemata Harbour showing general extent.

Mechanics bays. Considerable reclamation along this latter shore has rectified a long stretch of the coast, but the line of low cliffs behind the reclaimed areas shows that this section of the coast formerly was also broken by numerous small bays and inlets. Further to the west the harbour opens out, becomes extended in a north-south direction, and fades into sinuous creeks that are tidal for many miles from their entries into the harbour. This paper is concerned mainly with the east-west seaward portion of the harbour between Kauri Point and North Head (Fig. 2).

Except at the heads of the larger inlets the coast is steeply cliffed and fringed by broad rock platforms cut between tidal limits and in some places thinly veneered with muds. This is so even in the more sheltered bays where the waves have little corrosive power. In a few short stretches the coastal rocks are of volcanic materials from some of the sub-Recent basaltic volcanoes of the district, and in a few areas Pleistocene or Recent sediments build the coast, but in the main the cliffs are composed of sandsone and mudstone of the Waitemata Formation (Altonian). As has been pointed out by Bartrum (1926) and by the writer (Searle, 1948), the subaerial frittering of the clayey sediments of this formation has been a major factor in the rapid retreat of the cliffs and in the formation of the wide rock-cut shore platforms. Headlands and offshore rock reefs usually result from the cropping out along the coast of massive resistant andesitic grit beds which are widespread members of the Waitemata Formation.

There are few islands and they are all small. Watchman Island

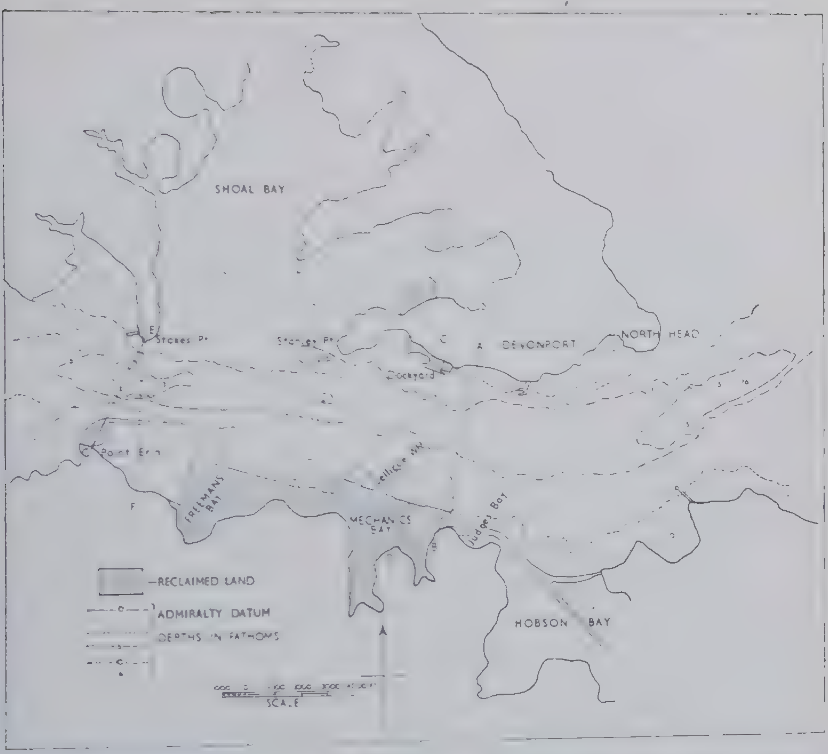

FIG. 2.—The seaward portion of Waitemata Harbour east of Stokes Point showing lines of section, etc.

(Sentinel Rock) is a residual of Waitemata sediments with an elevation of 27 ft above M.S.L.; the dissected surface of the island appears to be a remnant of the 40 ft terrace prominent on the isthmus. Traherne and Pollen islands in the upper harbour have elevations of only 11 ft to 12 ft above the same datum and seem to be remnants of a low terrace built of ?Recent sediments that had considerable extent near Whau estuaray.

Generally, the floor of the harbour is moderately flat and smoothly dished, and apart from marginal and a few other areas of exposed bedrock, it is thickly mantled with mud. The waters with depths greater than 2 fathoms L.W.S.T., as shown on Admiralty Chart 1970 (Auckland Harbour) are restricted to a well-defined watercourse, little more than $\frac{3}{4}$ mile in width, which sweeps closer to the northern than to the southern shore. This asymmetry in the underwater valley profile is clearly apparent in the cross-sections of Fig. 3. The Auckland Harbour Board Charts E-758/1 and 2 show that the main thread of tidal

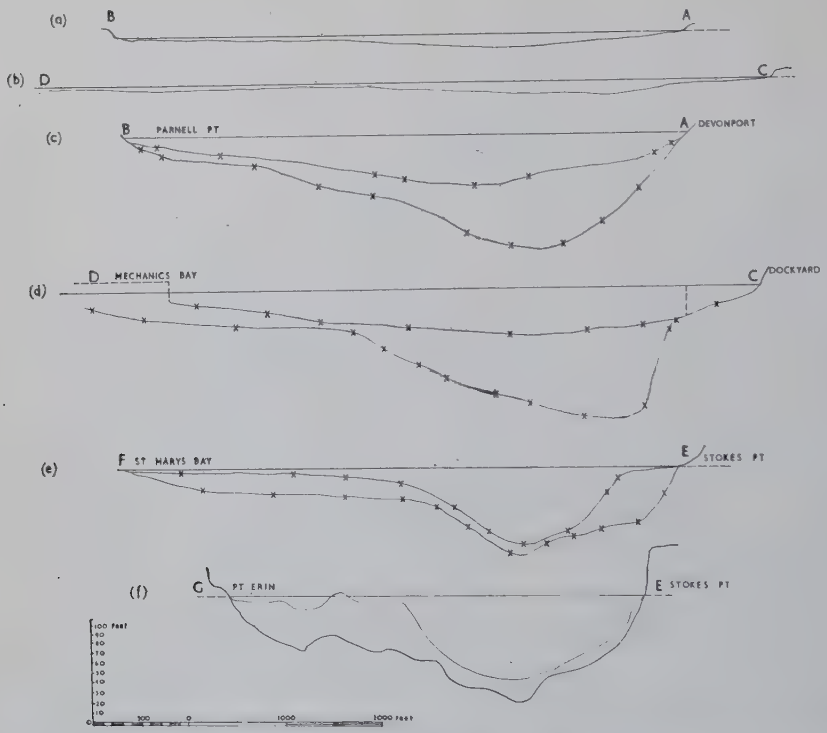

FIG. 3.—Profiles constructed on lines of section to show harbour bed and bedrock [fill, indicated by broken lines, is shown in (c) only]: (a) and (b)—natural scale; (c), (d), (e), and (f)—vertical scale exaggerated × 10.

flow follows this channel with a velocity of 2 knots at half-tide, there being no appreciable difference between the rates of ebb and flood. Tidal range for mean spring tides is 11 ft and the range between highest and lowest recorded tides is 1 ft.

A number of deep hollows elongated parallel to the directions of tidal flow are an interesting feature in the bed of the main channel. The largest of these is at the entrance to the harbour and has a maximum depth, as shown by Admiralty Chart 1970, of more than 16 fathoms L.W.S.T.; that is, it is some 36 ft (or more than 50%) deeper than the general depth of the channel. There are three other such deeps within the harbour: a small area off Stanley Point where the sounding is noted as "more than 95 ft on the A.H.B. chart Z-1/16; others off Kauri Point and Stokes Point where the depths, according to Admiralty Chart 1970, are greater than 13 fathoms L.W.S.T. The origin of these deeps is doubtless due to scour or to nondeposition of sediments as a result of local turbulence. Engineers of the Auckland Harbour Board on several occasions have dumped large quantities of spoil in the deep off Stanley Point with the intention of filling it, but soundings a few weeks later have shown each time that the filling has been removed, and there have been no indications of its deposition near at hand. The A.H.B. tidal flow charts E-871/- and /2 do not reveal any evidence of vortex movement in the tidal currents of the ebb or flood, so it seems probable that the vertical movement necessary to lift debris from these deeps stems from horizontal rolls rather than from vertical eddies in the tidal current.

Records of the rates of deposition inside the harbour are scanty. Investigations by Harbour Board engineers suggest that accretion is not rapid. In the vicinity of the wharves records over a few years show that in the sluggish water of the dredged berths the rate may be as much as 4 inches to 6 inches a year, but on the high banks under the wharves and also beyond their ends where the tidal flow is relatively strong, sediment is accummulating at a negligible rate.

Prickings and drillings[1] carried out along the lines of section shown on the accompanying map (Fig. 2) show that the ancient valley occupied by Waitemata Harbour has been partly infilled by the deposition of sediments. In places the thickness of this fill is as much as 50 ft but elsewhere, as along the line of the harbour bridge (Fig. 3f.), little or no mud occurs and bed rock is exposed over the greater part of the section. Cross-sections have been constructed (Fig. 3) on the data available to show the relation of the present harbour floor to the ancient valley bottom carved in the rocks of the Waitemata Formation. Two profiles (a) and (b) are given, in which the horizontal and vertical scales are the same in order, to show the true form of the valley and of the surface of its fill. In addition, on each line of section a profile has been drawn in which the vertical scale is ten times that of the horizontal. This exaggeration in vertical scale has been necessary to make apparent any changes in slope that are obscured by the drawing on a natural scale of a feature which is so shallow with respect to its width.

The bulk of the material of the fill is water-saturated unconsolidated modern mud. If the low sea-level of the Last Glaciation maximum is accepted as the end of the Pleistocene, this mud must be regarded as of Recent age and the product of the succeeding rise of sea-level during the Flandrian transgression. The descriptions of the cores on some of the bore records, however, do not preclude the possibility that some of the silts at the base of these muds may be Pleistocene in age. Some bore logs describe sediments such as light coloured and peaty clays—lithologies that locally are commonly associated with Pleistocene formations which have been recognized as part of the harbour bed in the Shoal Bay and upper harbour areas. Nevertheless, bore cores from these clays in the sections under consideration cannot with any degree of confidence be correlated with undoubted

Pleistocene beds. Until more definite evidence is available it is proposed that the whole of the fill in the seaward portion of the main valley should be regarded as emplaced during Recent times as defined above. The uppermost material is fine in grain. blue-black in colour, and lacks coherence. The deeper silt-to-sand grades are firmer, but still poorly consolidated, lighter in colour, and commonly dry out to an ash-grey silt.

The sections in Fig. 3 show the present harbour bed as a relatively shallow feature with smoothly shelving walls that steepen very gradually towards the main channel which is situated directly above the older channel of the ancient valley. In the true-scale sections this ancient valley is seen also to have a shallow form with smooth flanks, but the sections with enlarged vertical scale reveal a rock bottom with distinct shoulders where the slope falls off to the channel bottom. These sections clearly suggest a well-defined rock-cut bench on the south shore at an altitude of 30 ft to 40 ft below mean sea-level. In the Mechanics Bay-Dockyard profile (Fig. 2d), the bench has a width of less than half a mile and in the St. Mary's Bay-Stokes Point profile it appears to be much wider. However, the latter section is not drawn normal to the line of the valley, so the appearance of width may be

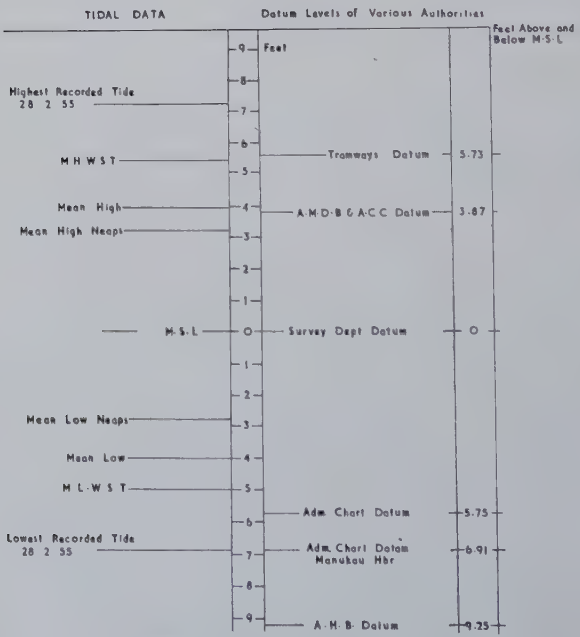

FIG. 4.—Tidal data for Waitemata Harbour, and datum levels employed by local authorities.

deceptive. The smooth bedrock bench is too prominent and too persistent in the reconstructed profiles to be dismissed as unimportant.

Turner and Bartrum (1925) recorded "broad subaqueous benches that exist a few feet below low water level" in the neighbourhood of the wharves, and correlated these features with platforms in Shoal Bay which they describe as "a little below what is present sea-level". Turner and Bartum suggested that these underwater benches may be explained as floodplains carved by small streams that debouched into the main valley "prior to submergence". In earlier work of this type much confusion has arisen from the inexact statement of datum levels and, indeed, still arises from the use of different datum levels employed by different authorities operating in the district—a number of these are shown in the table (Fig. 4). The Shoal Bay platform is almost wholly exposed above the level of low water spring tides, while the bench near the Auckland wharves recorded by Turner and Bartrum would seem to be a few feet below the same level. Contrary to their belief, the writer considers that normal erosion under the control of seas at their present, or even slightly higher levels satisfactorily explains the carving of platforms such as those just described.

The prominent bedrock benches which appear in the cross-sections of Fig. 3 are certainly not of the same nature as those just considered, and it seems impossible that their planation could have taken place with sea-level at its present height. Shore platforms within the harbour that are obviously related to present-day conditions extend very little below L.W.S.T. and thus provide clear evidence that modern planation along the harbour coast is confined almost wholly to the tidal range. Furthermore, the smooth bedrock platforms shown in the sections are covered in places by muds 20 feet deep and the profile developed on the surface of this fill appears to be graded with respect to the modern-cut platforms nearer the shore. The confused and irregular disposition of the strata on which the deeper platforms are cut rules out any possibility that they are structural benches. The obvious explanation is to regard them as benches carved during an episode of stillstand when sea-levels were at an altitude some thirty feet below those of today.

Survey work east of Jellicoe Wharf indicates that the seaward extensions of the small stream systems draining into Mechanic's Bay and Judge's Bay are deeply entrenched below the surface of these bedrock benches and suggests further that their channels are more or less graded to their points of confluence with the main east-west valley bottom. The shoulders of these minor stream valleys against the bench they traverse seem to be moderately sharp and the walls of the valleys fairly steep. The picture as a whole suggests that the benches were formed earlier and that streams later carved the small valleys across them. If this explanation is accepted, then it is necessary to assume that the benches were cut during a period of stillstand which occurred prior to the glacial maximum and at a time when the falling sea-level had established a temporary shoreline about 30 feet below the present level. On the other hand, there would appear to be no evidence that would conflict with an hypothesis that the benches were developed on a terrain in which the tributary valleys were already graded to the lowest sea-levels of the glacial maximum. If this is the case, then the benches would have been cut later when a hiatus occurred in the rise of sea-level during the Flandrian transgression which followed the glacial maximum. In either case the evidence from this portion of Waitemata Harbour shows that the sequence of Pleistocene and Recent terrace-forming processes deduced from the adjacent land areas must be modified, either before or after the Flandrian transgression, in order to accommodate the formation of the benches described in this paper.

ACKNOWLEDGEMENT

The thanks of the writer are due to his colleague, Dr R. N. Brothers, who read the script and offered helpful comment.

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A LOWER MESOZOIC ANNELID FROM ROCK POINT, SOUTH-WESTERN WELLINGTON, NEW ZEALAND

By B. D. Webby, Geology Department, Victoria University of Wellington.

(Received for publication, 24 June 1958)

Summary

Titahia corrugata, a new genus and species of agglutinating annelid (Terebellidae), is described from the greywacke-argillite rocks of Wellington.

Introduction

In the course of geological investigations near Titahi Bay, fossil worm tubes were found that differ markedly from the well-known annelid *Terebellina (Torlessia) mackayi* (Bather).

The tubes are embedded in argillite of an alternating greywacke and argillite succession, which forms a part of the extensive, sparsely fossiliferous, undifferentiated Jurassic-Triassic-Permian (9A) rocks of New Zealand. The rocks of south-western Wellington are probably of Triassic or Lower Jurassic age, as they contain *Terebellina (Torlessia) mackayi* (Bather, 1906; Jaworski, 1915).

SYSTEMATICS

ANNELIDA

Family Terebellidae

Genus Titahia nov.

Type: ***Titahia corrugata*** n.sp. Lower Mesozoic, N.Z.

Tube large, very slightly tapered along its length, with prominent longitundinal ribs. Tube wall siliceous, formed by a cemented aggregation of sand grains. Attitude, lying in the plane of bedding.

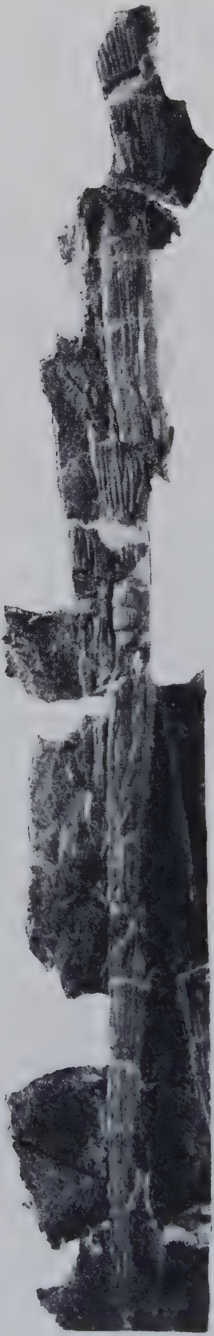
Titahia differs markedly from *Terebellina* in its larger size, thicker-tube wall, and prominent longitudinal ribs.

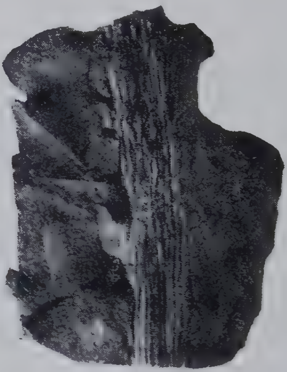
The generic name *Titahia* is from the Maori name of a bay 3 miles north-east of the type locality, and is to be considered feminine.

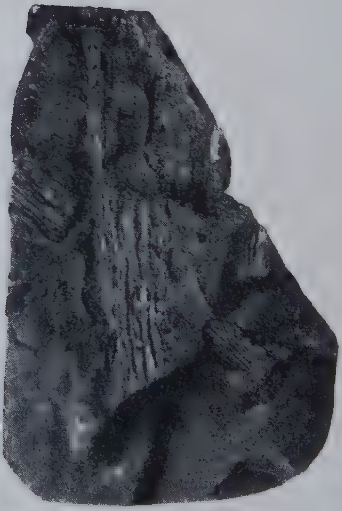
Titahia corrugata Webby n.sp. (Figs 1 to 5).

A large, straight, very slightly tapered worm tube, elliptical in tranverse section, probably due to compaction. Externally, tube

N.Z. J. Geol. Geophys. 1 : 509-13.







FIGS 1, 2, 3.—*Titahia corrugata* Webby, n.gen., n.sp.

FIG. 1.—Holotype, × $\frac{7}{8}$.

FIG. 2.—Paratype A, × 1.

FIG. 3.—Paratype B, × 1.

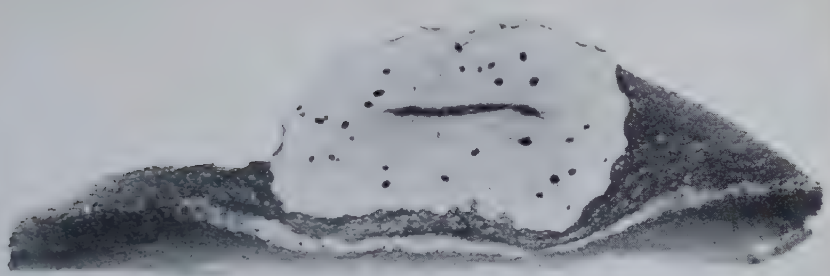


FIG. 4.—*Titahia corrugata* Webby, n.gen., n.sp., paratype A, transverse section × 7.

sculptured by 18 to 24 longitudinal ribs. Ribs strong, linear, even to gently undulatory, with few bifurcations. Interspaces varying from deep, narrow to shallow, broad grooves. Thin sections show that the tube consists of mainly fine, angular quartz grains (20 to 50μ grain size), and a few large, angular pyrite grains (50 to 200μ grain size). Whole tube without internal structure, being a cemented aggregate of silt grains. Internal surface of tube smooth. Lumen greatly compressed.

DIMENSIONS: Holotype—length 205 mm, maximum diameter 2·2 to 9·6 mm, minimum diameter 1·2 to 2·6 mm, single wall thickness 0·9 mm.

Paratype A—length 45 mm, maximum diameter 6·9 to 7·1 mm, minimum diameter 2·0 to 3·4 mm, single wall thickness 0·9 to 1·6 mm.

Paratype B—length 50 mm, maximum diameter 7·5 mm, minimum diameter 2·0 to 3·8 mm, single wall thickness 1·0 to 1·8 mm.

Holotype and paratypes in the New Zealand Geological Survey Collection. Other paratypes in the Geology Department, Victoria University of Wellington.

LOCALITY: Alternating greywacke and argillite strata (Lower Mesozoic) of Rock Point, south-western Wellington (N 160/347408).

REMARKS: *Titahia corrugata* lies in random directions in the plane of bedding. Tubes are commonly associated together. The tubes are enclosed in poorly sorted, well indurated silty-mud (argillite). Lumens now contain claystone.

The specimens were compared with *Dentalium batheri* (Finlay) (= *D. huttoni* of Bather, not of Kirk). *D. huttoni*, as originally described by Bather (1905), differs from *T. corrugata* in its strong

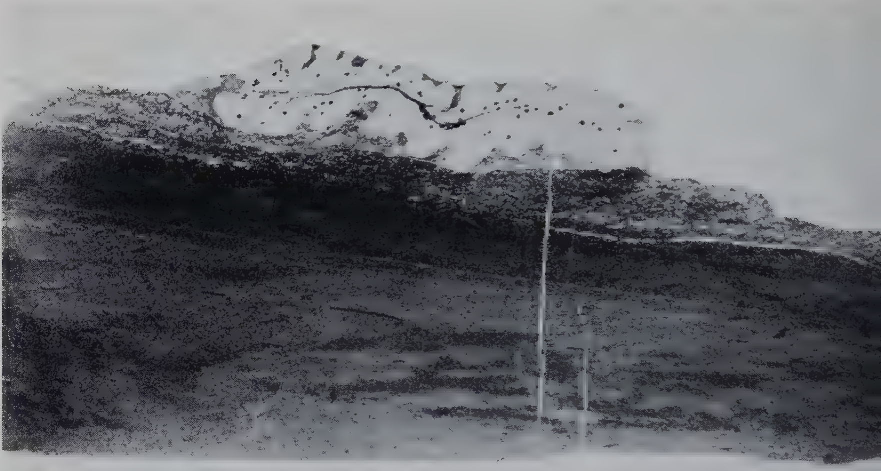


FIG. 5.—*Titahia corrugata* Webby, n.gen., n.sp., paratype B, transverse section × 7½.

Photos: M. D. King

curvature and rapid taper. Bather's type specimens, which are located in the British Museum Collection, were recently re-examined by Dr L. R. Cox, who remarks (pers. comm.) that the holotype is calcareous, and the paratypes are structureless casts with no tubes preserved. They thus differ from the siliceous tubes of *T. corrugata*.

A few early records of *Dentalium* from undifferentiated Jurassic-Triassic-Permian (9A) rocks of New Zealand may be congeneric with *Titahia corrugata*. Crawford (1868, p. 308) discovered fossils which he supposed to be "either *Theca* or *Dentalium;* and some vermiform casts, probably *Tentaculites*", from Belmont Hill, west of the Hutt Valley. Cox (1877, p. 78) recorded the discovery of a *Dentalium* in the Maitai Series of the Taipo Ranges, Westland. Morgan (1908, p. 80) recorded and sketched (Plate XVIII, fig. 4) a strongly ribbed, curved *Dentalium* found on the main divide just north of Mungo Saddle, North Westland. Critical comparisons of these reported specimens cannot be made, as none was collected.

According to Mr J. D. Campbell (pers. comm.) a longitudinally striated form similar to *Titahia corrugata* is associated with *Terebellina (Torlessia) mackayi* in strata on the north-west face of Mt Torlesse, Canterbury. Mr Campbell has always considered this form to be *Dentalium batheri* (Finlay) (= *D. huttoni* Bather, not of Kirk).

ACKNOWLEDGEMENTS

The writer is indebted to Dr C. A. Fleming for general guidance and advice. Thanks are also due to Dr L. R. Cox of the British Museum (Natural History) for supplying details of type specimens, and to Mr J. D. Campbell for information on the distribution of certain Triassic fossils in Canterbury.

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NOTES ON FOUR MINOR SULPHIDE PROSPECTS NEAR COROMANDEL

By David Kear, New Zealand Geological Survey, Department of Scientific and Industrial Research

(Received for publication, 27 May 1958)

Summary

Four sulphide prospects near Coromandel proved, on investigation, to be either too low-grade or too small to be economic. However, they include examples of preferential pyritization of carbonaceous beds, of very rich pyritization and associated intense propylitization that is apparently structurally rather than lithologically controlled; and of areal pyritization of andesites (2% to 6% pyrite).

Introduction

Members of the Coromandel Prospectors Association are still very active, and ensure that local outcrops of possible economic importance are brought to the attention of the Geological Survey. The present note records some interesting results of investigations into four such prospects during the increased interest during 1954-1955 in sulphide deposits. None proved to be an economic source of sulphur.

General Geology

Fraser and Adams (1907) mapped the rocks near Coromandel either as pre-Tertiary greywackes and argillites of the Tokatea Hill "Series", or as Tertiary Volcanic Rocks of the "First", "Second", or "Third" Period (together with minor areas of Tertiary Torehina "Series" and Quaternary rocks). Three of the present sulphide prospects are within areas mapped as "Volcanic Rocks of the First Period", and the fourth (Aitken Creek) is within the Tokatea Hill "Series". The locality map presented here (Fig. 1A) includes Fraser and Adams' mapping in very simplified form.

Inland Road Prospect

Fraser and Adams (1907, p. 66) refer to a silicified and pyritized coaly band, over 2 ft in thickness, in Kapanga Mine. They suggested that it might be continuous with carbonaceous beds of the Triumph Mine area, and that it indicated a "considerable period of quiescene between successive eruptions" of the "First Period Volcanics". Such a pyritized carbonaceous bed is exposed within apparently unmineralized andesites along the "Inland Road" between 1¼ and 1½ miles north of

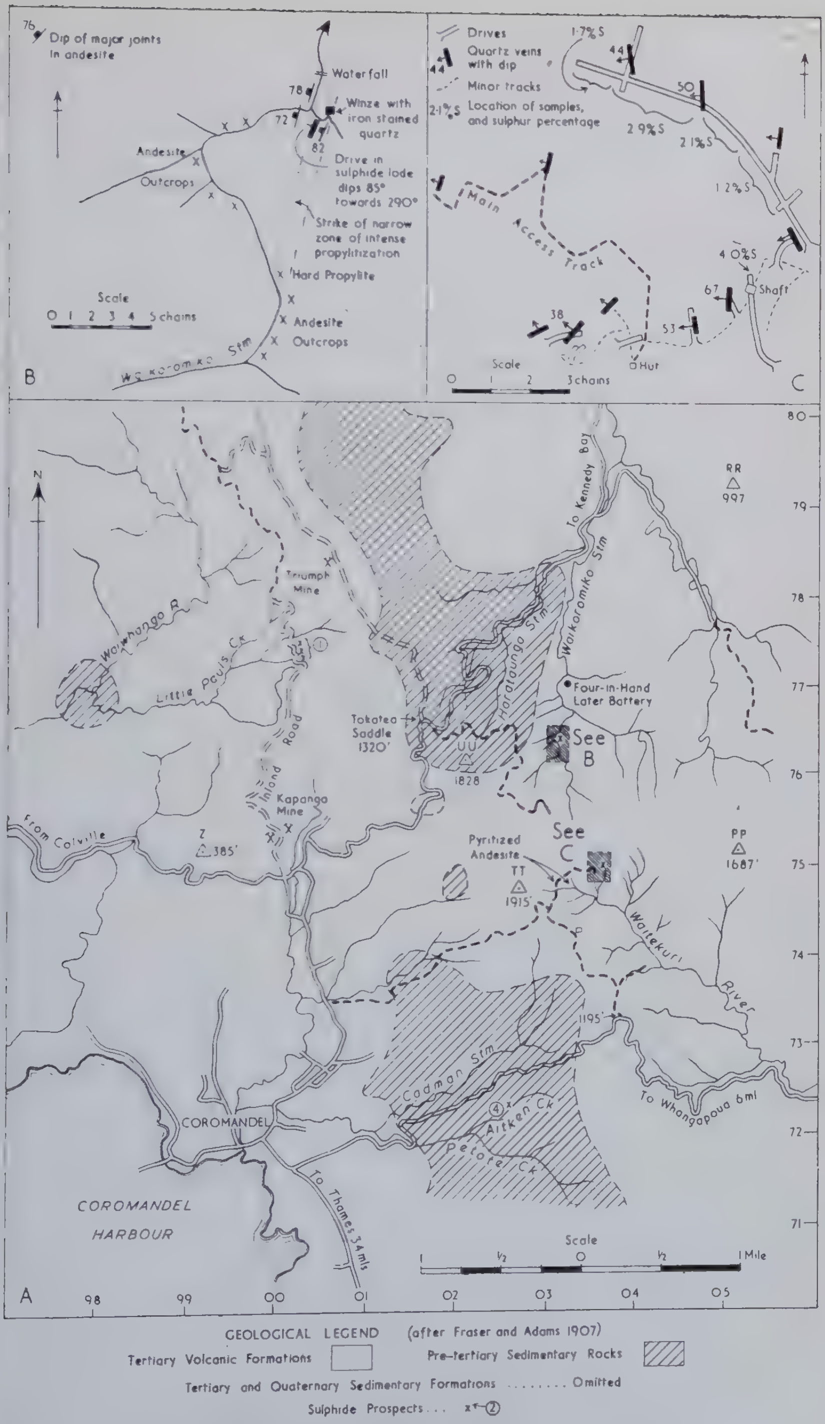

FIG. 1A.—Locality map, with simplified geology.
B.—Detail of Waikoromiko Stream Prospect.
C.—Detail of Waitekuri River Prospect.

the Colville Road junction (Fig. 1A, grid reference N40/002774). The bed is rich in sulphur, but is far too thin (up to 1 ft only) to be workable. Samples from these carbonaceous beds (N40/f500-1) yielded no plant microfossils (Mrs W. P. Tolley, pers. comm.).

WAIKOROMIKO STREAM PROSPECT

An abandoned drive in Waikoromiko Stream, 50 chains east-north-east of Trig UU (Figs 1A and B, grid reference N40/031765), exposes a lode of granular pyrite, nearly 5 ft wide, that dips at 85° towards 275°. Half a chain north-east, iron-stained quartz has been removed from a winze that is at least 20 ft deep. Both the drive and winze are within a narrow zone of intense propylitization that strikes similarly to the lode and reappears in the stream 8 chains to the south (Fig. 1B). Representative samples from the lode and from 4½ ft of the footwall, and a grab sample from near the winze, contained 35·7%, 3·8%, and 7·4% of sulphur respectively; and the lode contained (Mr H. Crawford, assayer) 2½ dwt gold and 10 dwt silver per ton. Although these figures indicate considerable local enrichment in sulphides, the zone is too narrow and averages too low a grade to represent an economic deposit.

Beyond the zone of intense propylitization, grey porphyritic hornblende andesite, containing conspicuous but fine cubes of pyrite, is exposed in the creek. The content of pyrite cubes is approximately constant within the area shown in Fig. 1B, and a composite sample from near the drive (representing 1 chain of stream outcrops) analysed 1·2% sulphur. Major joints within the andesite dip almost identically to the lode (Fig. 1B).

WAITEKURI RIVER PROSPECT

Messrs Lillis and Kayser ("L.K.P. Prospectors") are actively re-opening a gold area in the headwaters of Waitekuri River (Figs 1A and C, grid reference N40/035749), which was worked on behalf of the Kauri Co. 60 years ago. Two sets of auriferous quartz veins are present (up to 3 ft wide), one dipping west and the other north-west at 35° to 70° (Fig. 1C). The walls of the longest drive were sampled by Mr A. Fleming, who is prospecting for base metals a little down river, and the resulting analysis showed 13·9% sulphur. All the andesite country rock contains small cubes of pyrite, and the mineral is concentrated locally in fine fissures. Four composite samples, each comprising many closely and regularly spaced grab samples of equal bulk, were collected by the author from the same walls and showed a range of uneconomic sulphur contents of 1·2% to 2·9% (Fig. 1C). This suggests that Mr Fleming's sample was essentially of material from the richer fissures. A channel sample of freshly broken rock was collected from a drive to the south (Fig. 1C) and contained 4·0% sulphur. Separate assays of these five samples showed 5 to 7 grains gold and 2 to 5 dwts silver per ton.

AITKEN CREEK LEAD-ZINC REEF

An old mine mouth, reputedly on the north side of Aitken Creek about half a mile downstream from the prominent andesite bluffs, could not be re-located. However, a narrow low-grade base metal reef, striking west of north, was sampled in the same area (Fig. 1, grid reference N40/025722). Both galena and sphalerite were recognized, and the sample's analysis showed 10·0% zinc, 1·7% lead, 0·005% silver, and 0·06% cadmium. The reef, however, was too thin and too low-grade to be an economic source of sulphur.

Several lead-zinc lodes have been reported from Petote Creek to the south (Mr L. Davis, Coromandel, pers. comm.).

CONCLUSIONS

Although no prospect proved of economic importance, the following points are of geological interest:

(1) Pyritization at the Inland Road Prospect is restricted to the thin carbonaceous bed—the enclosing andesites being relatively unaffected (compare the preferential pyritization of carbonaceous material at the Kauaeranga deposit—Kear, 1957, pp. 493-4).

(2) At the Waikoromiko Stream prospect, the strikes of the lode, of the zone of intense propylitization, and of the andesite joints are all closely similar. In addition, the dips of the lode and of the joints are both close to vertical. It thus appears that the rich pyritization and the proplitization were structurally rather than lithologically controlled. This is in apparent contrast to the presumed lithological control of marcasite and pyrite enrichment within the Mineralized Belt of Kauaeranga (Kear, 1957, p. 494). It is likely, however, that all such propylitized and mineralized belts are basically structurally controlled and that differential mineralization within each may be controlled by lithology.

(3) The "normal" andesites of the Waikoromiko Stream and Waitekuri River prospects contain 1·2% to 2·9% sulphur, mainly as pyrite. This compares well to the probable minimum of 2% sulphur (again mainly as pyrite) in the lowest grade andesites of the Kauaeranga mineralized belt (Kear, 1957, p. 488). Whilst extremely low compared with sulphur ore deposits, these figures are high for andesites that are outside the immediate areas of mining. Andesites from Yellowstone National Park and Alaska contain 0·05% and 0·06% FeS_2 (Clarke, 1924, p. 458); from Thames, 0·12% SO_3 (Fraser, 1910, p. 24); from Waihi, no FeS_2 (Morgan, 1924, p. 61); from Kawhia, 0·02% S (Henderson and Grange, 1926, pp. 70-1); from Rotorua, 0·03% S (Grange, 1937, p. 67); and from Mount Somers, 0·02% to 0·04% S (Speight, 1938, p. 25). The present values give a quantitative figure of 1·2% to 2·9% sulphur (say 2% to 6% pyrite) for the pyritization that has long been recognized (e.g., Morgan, 1924, p. 84) as accompanying propylitization of the Hauraki Goldfields. Substantial areas can

be affected, for the Kauaeranga mineralized belt covers at least 150 acres, and the Waikoromiko Stream and Waitekuri River prospects might well be parts of a single mineralized area.

ACKNOWLEDGEMENTS

The author's thanks are due to Messrs Allington, Lillis, and Kayser for their hospitality and their company in the field; to Mr H. Crawford for the assay result attributed to him, and to the Dominion Analyst for the remainder of the assays and analyses quoted.

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SOME OBSERVATIONS ON NIGHT-TIME IONOSPHERIC STORMS AT CHRISTCHURCH

By RUTH F. MASON, Geophysical Observatory, Department Scientific and Industrial Research, Christchurch.

(Received for publication, 11 February 1958)

Summary

Data from Ionograms are discussed in relation to the description of night-time storms at Christchurch. A consideration of seasonal variation shows that in winter, storms have features not noticeable at other seasons. Electron distributions are calculated for the early hours of both severe and moderate storms; all show an initial increase in the number of electrons up to maximum density level prior to the storm decrease normal for this latitude.

INTRODUCTION

For this preliminary investigation of ionospheric storms, at Christchurch (Lat. 43° 34′ S., Long. 172° 48′ E.) night-time storms were selected for the following reasons:

(1) No ion production takes place during the storm.

(2) The electron distribution is simpler than during daytime, as only one layer is usually present.

(3) Only when a lower layer forms in the course of a storm is interaction between layers possible.

There are therefore fewer variables to be taken into account when interpreting stormy ionograms.

The main object of the work was to evaluate the parameters obtainable directly or indirectly from ionograms, for their relative merits in describing night-time storms. Both seasonal and diurnal variations were studied. as were relationships with magnetic storms, and variations in electron density distributions as derived from reduced records. The followng parameters were investigated: height and frequency changes, visible electron content, presence of oblique reflections, presence of a night-time lower layer, and time from sudden commencement to beginning of ionospheric storm. Spread echoes were not considered separately, as there is already a great deal of published information correlating them with other phenomena (W. Dieminger, 1951; R. W. Wright, J. R. Koster, and N. J. Skinner, 1956; G. Reber, 1956).

The years 1947 through 1951 were selected for the investigation, as they cover a suitable phase of the sunspot cycle and a reasonably complete set of half-hourly records is available at Christchurch. The corresponding magnetic storms commencing during the night hours were studied from records taken at Amberley (Lat. 43° 10′ S., Long. 172° 43′ E.). Their distribution over the period is given in Table I.

Table 1.—Number of Magnetic Storms Commencing During the Night Hours. Figures in parentheses indicate the number of corresponding ionospheric records that are missing, illegible, or very much disturbed by a preceeding storm.

Year	No. Magnetic Storms K4		No. Magnetic Storms K5		No. Magnetic Storms K6+	
	S.C.	no S.C.	S.C.	no S.C.	S.C.	no S.C.
1947	1	—	6(2)	2	4	—
1948	4	5(1)	7(2)	4(1)	1	—
1949	4(1)	4	6	2	3	—
1950	3	4(1)	8(1)	6	2	1
1951	1	9(5)	4(1)	6(1)	2	—
	13(1)	22(7)	31(6)	20(2)	12	1

Relationship With K-Index of Magnetic Storms

Initially, magnetic storms with K-Index 5 were used to locate ionospheric disturbances. The use of this K-Index classification did not prove entirely satisfactory, because although the correlation between the occurrence of magnetic and ionospheric storms is good, their relative magnitudes are not always in agreement. The disagreement is probably due to a number of factors, both magnetic and ionospheric. One of these is the nature of the K-Index, which measures only the maximum range described by a magnetic component, whereas the fluctuations within this range may have some bearing on ionospheric conditions. Another factor is the length of time between the beginning of the positive and the negative phases; a very short interval often results in a high K-Index, while if the interval is very long the maximum K-Index may not occur till the following day or night, the indices from the S.C. till that time indicating only slight disturbance.

Commencement Times of Ionospheric Storms

Ionospheric behaviour is considered in two categories; firstly, ionospheric disturbances that correspond to magnetic storms commencing during the night hours, and secondly, ionospheric behaviour corresponding to magnetic storms commencing prior to sunset, i.e., 12 h to 18 h local time.

(1) It is generally agreed that a typical ionospheric storm first becomes evident during the change from the positive to the negative phase of a magnetic storm, this being the period for which the maximum K-Index is generally recorded. As storms do not always follow

this pattern exactly, a simple measure of the time between the sudden commencement and the first appearance of ionospheric disturbance was made. During the five-year period there were 48 storms which had night-time sudden commencements and for which ionospheric records were available. Of these, seven did not have distinct ionospheric disturbances associated with them on the first night. For the remaining 41 storms the time difference varied from 0 to 5 hr, two-thirds (28 storms) showing an ionospheric effect within an hour of the sudden commencement. This rapid onset of storm conditions was most marked in winter, when only one out of 14 storms had a time lag of more than 1 hr (and that being a minor storm, its precise commencement was difficult to locate). During equinox, a lag greater than 2 hr was common, occurring in 11 out of 20 storms. This delay was accompanied by a corresponding lapse in magnetic activity after the S.C. in eight of the 11 "slow" storms; in the other three the ionospheric lag accompanied a K-Index of 4 or higher.

(2) Of the magnetic storms commencing in the 12 h to 18 h period only those with $K \geqq 5$ were used to identify ionospheric disturbances. In this period heights of ionospheric layers did not appear to be affected during the daylight hours, nor was any change in the the shape of the h′f trace apparent. The only obvious changes were in critical frequency, and these fell roughly into two groups; (a) a slow but steady decrease, starting in daytime and continuing into the night, and (b) a sudden decrease, with a subsequent increase or a continuation of the diurnal variation pattern. The first type of frequency change, where the frequency decrease was of the order of 1 to 2 Mc/s, was more characteristic of winter months, and the sudden decrease, rarely greater than 1 Mc/s, was recorded more often in summer and in equinox.

TABLE 2.—Numbers of Storms With Slow and With Sudden Frequency Decreases Before Sunset.

Type of frequency change	Summer	Winter	Equinox
(a) Slow	—	4	4
(b) Sudden	6	1	12
No effect	4	5	8
Total	10	10	24

Of the 27 magnetic storms with sudden commencements and K-Indices > 5 that occurred during the 12 h to 18 h period, nine had no detectable effect on half-hourly ionospheric records, and 13 only the rapid frequency drop.

SEASONAL VARIATION IN SEVERITY OF NIGHT-TIME STORMS

The parameter used to compare the magnitudes of storms, classified according to year and season, was the maximum departure of the virtual height from the calm-night value for the same period durthe first night of the storm. The number of storms is of necessity small and when only sudden commencement storms are included, it is inadequate for complete analysis. It is hoped, however, that this study will indicate aspects of ionospheric behaviour for further investigation. On calm nights at Christchurch virtual heights show less fluctuation than do critical frequencies; seasonal height variations are only of the order of 30 Km, lower in winter and higher in summer. First night effects only are considered in order to minimize complications arising from daytime production and distribution of ionization. As a result, storms that are protracted rather than intense do not have a high rating in this classification (storms without S.C. often come into this category). Several equinoctial storms in particular, had high K-Indices but did not reach their maximum height departures till one or two days after their commencement.

TABLE 3.—Virtual Height Departures of Night-Time Ionospheric Storms Corresponding to Magnetic Storms with Max. K-Index $\geqq 4$.

	Summer				Equinox				Winter			
	S.C. Only		All Storms		S.C. Only		All Storms		S.C. Only		All Storms	
Year	No.	Max. dept	No.	Max. dept	No.	Max. dept	No.	Max. dept	No.	Max dept	No.	Max. dept
1947	3	100	3	100	4	50	4	50	4	200	6	150
1948	5	40	8	55	2	65	3	60	3	120	5	110
1949	4	85	8	65	5	80	6	85	3	90	4	65
1950	2	30	5	40	5	20	8	60	3	70	8	60
1951	—	—	2	50	4	110	10	60	1	80	4	55

The figures in the maximum departure columns are medians of the departures of individual storms. Medians instead of means, were used so as to include storms with too much disturbance for heights to be scaled. In seasonal groups where no such storms appear, the differences between means and medians are small. The decrease in storm activity with the declining sunspot cycle is evident in both summer and winter data. The large height departures recorded in winter were generally accompanied by comparable decreases in critical frequency. A possible explanation of the larger movements of the winter layer may lie in the low electron density, i.e., electrons being fewer in number would be displaced further by a disturbance of a certain magnitude than if their density had been greater.

The distribution of K-Indices did not show a seasonal basis,

OBLIQUE ECHOES

Non-vertical reflections in some form are associated with most storms. As is found with spread F, however, their detection is dependent on the sensitivity and the virtual height scale limit of the equipment. As a severe storm develops the oblique trace descends from the top of the ionogram until it merges with the main trace (see Fig. 1). It could therefore be assumed that in minor disturbances where the oblique trace does not appear on the ionogram, it is in fact beyond the upper limit of the recorder.

The oblique echo can be regarded either as the passage of a "cloud" of turbulence across the reflecting area, or as the approach of a turbulent front which reflects pulses in a similar manner to the aurorae, but at greater heights. Although the oblique trace is often a mass of scatter, its minimum height was scaled in some good examples. From the virtual heights of the oblique and main traces an estimate of the horizontal component of the velocity of the approaching front was calculated. No attempt was made to assign a particular direction to the front.

TABLE 4.

Type of Storm	Greatest range at which detected	Average velocity
Severe, Equinox 19/3/50 (K7)	370 Km.	8 Km/min.
Less severe, Winter 19/8/47 (K5)	440 Km.	2 Km/min.

In the case of the severe storm, heights of the oblique trace were measured until it coincided with the main trace, i.e., the "front" had reached the overhead position. In the other case the approach was slower and the least horizontal distance from the overhead position was 190 Km.

In addition to the decrease in virtual height of the oblique trace, both traces showed similar fluctuations in height (see Fig. 3); vertical movement therefore takes place simultaneously in the main layer and the front. The seasonal variation in the number of oblique reflections actually observed is expressed (in Table 5) as a percentage of the total number of storms in each season.

TABLE 5.

Summer	Winter	Equinox
26%	56%	33%

The winter maximum results from the large number of small

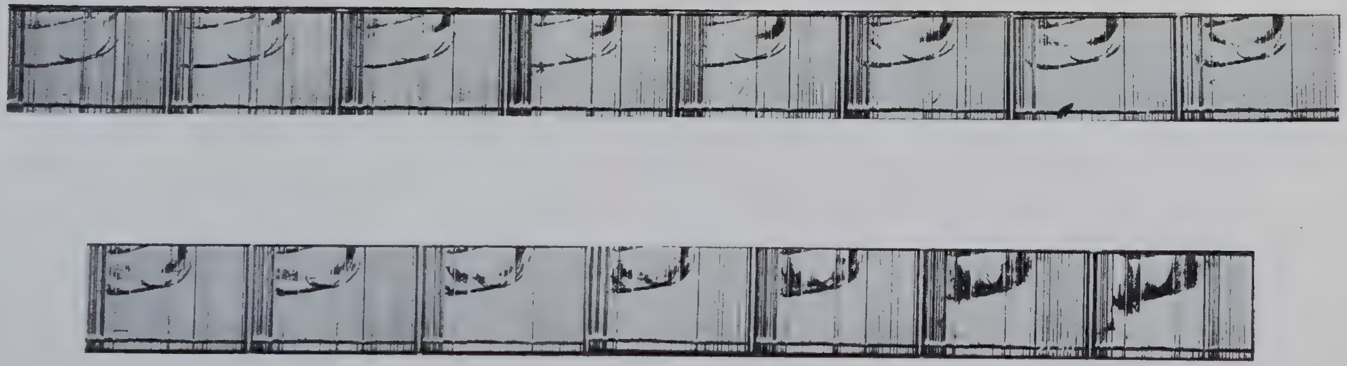

FIG. 1.—Frames at 4 min. intervals showing the descent of the oblique trace and formation of lower layer. 19/3/50.

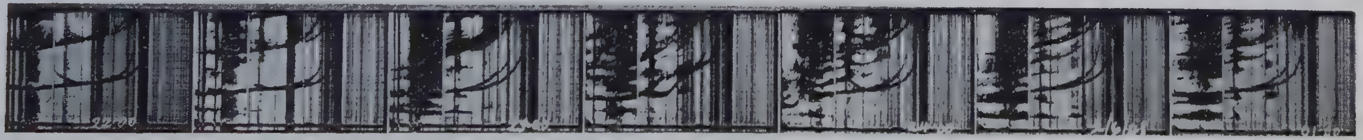

FIG. 2.—Frames at 30 min. intervals showing low-level stratification. 2/6/48.

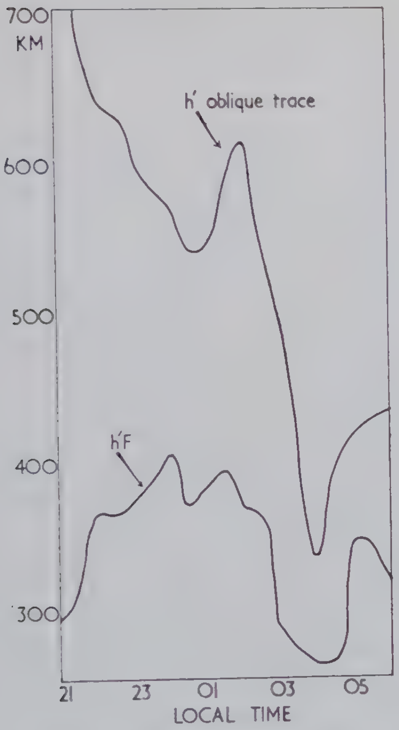

FIG. 3.—Simultaneous vertical height changes of the F-layer and oblique trace. 19/8/47.

storms having oblique echoes, whereas at other times almost all oblique reflections are recorded during major disturbances.

RETARDATION IN THE EXTRAORDINARY

This characteristic was present in all except 12 storms; none of these 12 showed any other definite storm feature on the first night. The retardation persists throughout a storm and has been taken as an indication of the presence of a lower layer when this is below the frequency limit of the recorder (1 Mc/s). It is one of the most dependable methods of detecting disturbed conditions in the ionosphere, but in itself gives no increases of the magnitude of the disturbance, except that it increases when the lower layer actually appears on the ionogram.

STRATIFICATION

Two distinct types of stratification appear on night-time records at Christchurch.

(a) The first and more common type is associated with oblique reflections close to, or coincident with, the main trace (see Fig. 1). This type of stratification is therefore a characteristic of severe storms, during which the front causing oblique echoes is close to the observing station. Although the lower layer may persist for several hours it has considerable spread and is often partly obscured by sporadic E.

(b) The second, low, type of stratification occurs at the lowest level of the F-region—about 200 to 220 Km. This phenomenon has been found only in winter, as this is the only season when the F-layer reaches this low level. It is associated with small disturbances where little or no oblique reflection is present. This low stratification is short lived and its development cannot be studied in detail in records taken at half-hourly intervals. Fig. 2 shows some stages in its formation.

CHANGES IN ELECTRON DISTRIBUTION

Electron density distributions were calculated from reduced records (King's method, 1954) for five storms. As ionogram traces nearly always deteriorate during the course of a storm, reductions were calculated for the first few hours only, and these do not necessarily include the period of maximum storm intensity.

TABLE 6.—Total Electron Content N of a Column 1 cm^2 in Area from the Base to the Maximum Density Level.

Date	N per cm^2 before S.C.	N max. per cm^2	N min. per cm^2
5/6/47	$3{\cdot}9 \times 10^{12}$	$5{\cdot}3 \times 10^{12}$	$2{\cdot}0 \times 10^{12}$
15/8/47	$3{\cdot}8 \times 10^{12}$	$4{\cdot}4 \times 10^{12}$	$2{\cdot}2 \times 10^{12}$
7/5/48	$7{\cdot}0 \times 10^{12}$	$8{\cdot}2 \times 10^{12}$	$< 2{\cdot}2 \times 10^{12}$
1/11/49	$4{\cdot}5 \times 10^{12}$	$5{\cdot}2 \times 10^{12}$	$2{\cdot}2 \times 10^{12}$
19/3/50	$4{\cdot}0 \times 10^{12}$	$5{\cdot}2 \times 10^{12}$	$< 2{\cdot}9 \times 10^{12}$

In all these storms the total visible electron content increases during the first hour after the sudden commencement, and then decreases rapidly. A typical example of these changes, together with corresponding changes in electron content on a calm night, is given in Figs. 4 and 5. The change in layer shape which causes the apparent increase is a small decrease in critical frequency combined with a considerable increase in height of maximum electron density, i.e., a thickening of the layer. By applying the above measures to a model parabolic

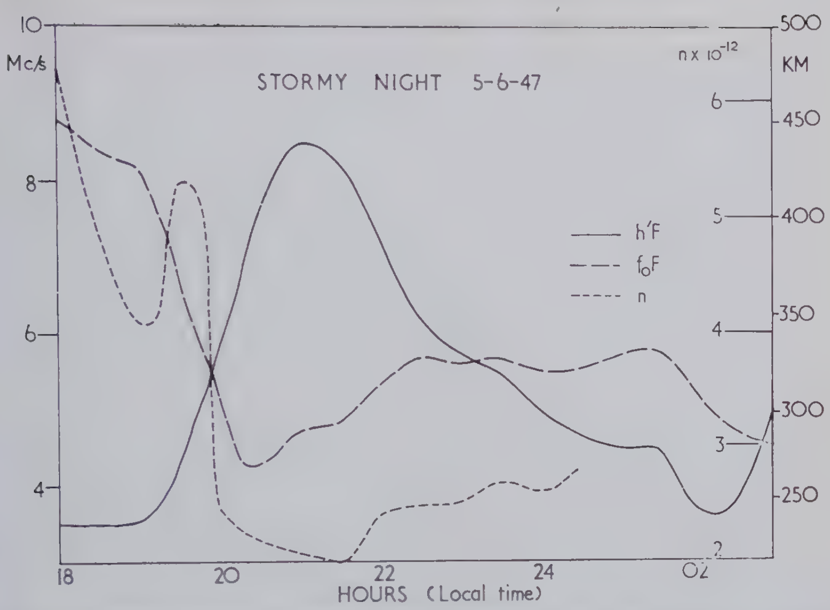

FIG. 4.—Changes in virtual height, critical frequency, and electron density during a night-time storm.

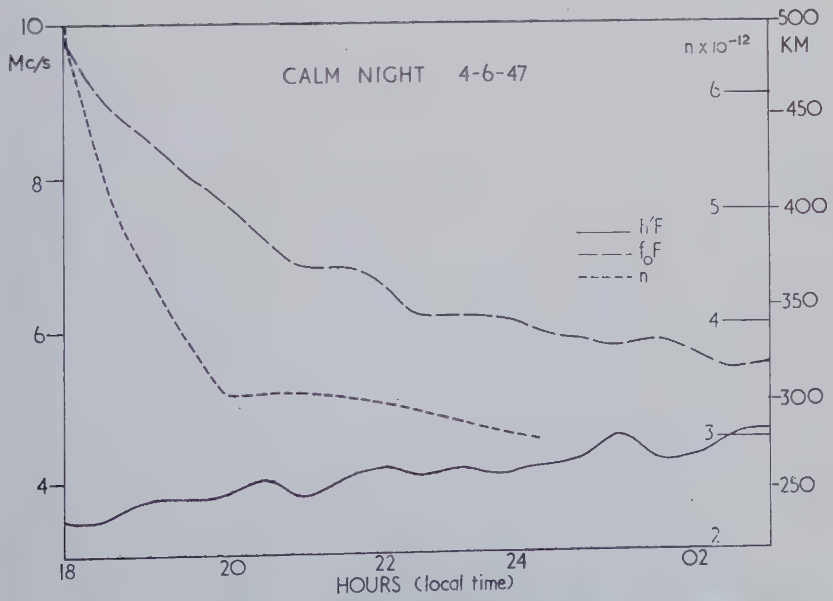

FIG. 5.—Changes in virtual height, critical frequency, and electron density during a comparable calm night.

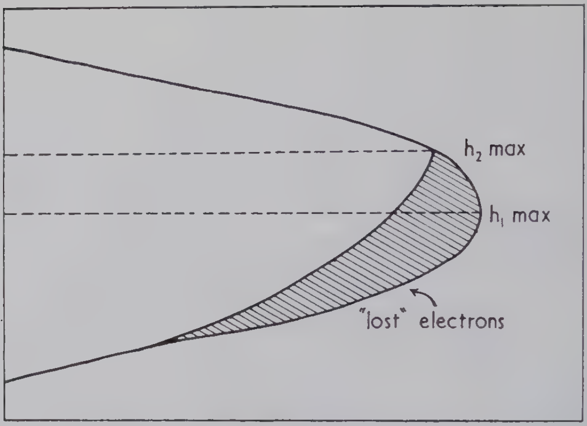

FIG. 6.—Model parabolic layer showing apparent increase in electron content caused by an increase in the height of maximum electron density.

layer it was found that a large number of electrons in the lower part of the layer can be lost, while up to the new height of maximum the total electron content increases (see Fig. 6).

DISCUSSION

From the examination of the various storm phenomena, the distinctive behaviour of night-time storms in winter is at once apparent. The rapid onset of the disturbance after a S.C. in the night hours and the slow decrease in critical frequency when the S.C. is in the afternoon, distinguish winter storms in their temporal aspect. The low electron content of the night-time winter ionosphere has already been mentioned as a possible explanation of the large height and frequency departures, especially at sunspot maximum. The prevalence of oblique reflections and the occurrence of low level stratification are other winter phenomena.

The use of oblique echoes to estimate the velocity and proximity of clouds of turbulence, or fronts, and the occurrence and persistence of the high type of stratification may be of assistance in classifying severe storms.

The changes in the shape of the electron density distribution at the beginning of a storm seem to indicate that the electrons near the height of maximum are affected first while those in the lower part of the layer react more slowly.

The retardation in the extraordinary, and its greater prominence when a lower layer appears on the ionogram, seems to indicate (by analogy with the formation of the daytime E-layer) that the formation of a lower layer is a vital part of the disturbance.

ACKNOWLEDGEMENTS

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A NOTE ON THE AGE OF THE JURASSIC FLORA OF OWAKA CREEK, SOUTH-EAST OTAGO, NEW ZEALAND

By I. G. SPEDEN, New Zealand Geological Survey, Department of Scientific and Industrial Research

(Received for publication, 21 March 1958)

Summary

The Owaka Creek flora, attributed to the Rhaetian or Lower Jurassic by Arber in 1917, is from beds that overlie Lower to Middle Callovian marine sediments, dated by ammonites, and is thus younger than previously thought.

Outcrops in the face at the back of the flood-plain on the south side of the Owaka River (Fig. 1), downstream from the main highway bridge, indicate the presence of a terrestrial-estuarine sequence some 500 ft thick, of interbedded mudstone, sandstone, greywacke, and thin, discontinuous, impure coal-seams. Large to small plant fragments, including leaf pinnules and carbonized wood remains, are abundant in many beds. The plant-beds locally overlie 400 ft of apparently unfossiliferous mudstone, which follows conformably above sandstones with *Haastina haastiana* Marwick, 1953. At Jacks Bay, where mudstone again overlies sandstone rock types with *H. haastiana*, the mudstone contains a faunule that includes *Nucula cuneiformis* (Sowerby, 1840), *Nuculana willetti* Marwick, 1953, *Camptonectes grandis* (Hector, 1886), *H. haastiana*, etc. (see Marwick, 1953, p. 27). Two miles along the strike to the south-east on the south-west facing slope of Jacobs Hills (N.Z.M.S. 1, sheet S184/497982), the stratigraphical position of the plant-beds is occupied by a sequence of marine sandstone and mudstone with numerous shell-beds of *H. haastiana*. Again, no plant-beds were found at or near the same stratigraphical position, either to the north-west of the Owaka Creek sequence or on the north-east side of the axis of the Southland Syncline (Fig. 2). No unconformities have been detected between the plant-bearing sequence and either the underlying marine beds or the overlying formation. The plant-beds are of restricted extent, and were probably formed during local shallowing to estuarine-terrestrial conditions of deposition. Their relationship is indicated in Fig. 2.

Plant impressions from Owaka were first collected by Hector in 1865. On Hector's instructions McKay (1877, p. 61) collected additional specimens in 1873. Arber (1917, p. 10) described the flora, listing nine species. During his mapping of the geology of the Glenomaru Survey District, Mackie (1935, p. 286) placed the plant-beds in the upper part of his J. 14 (Fig. 2).

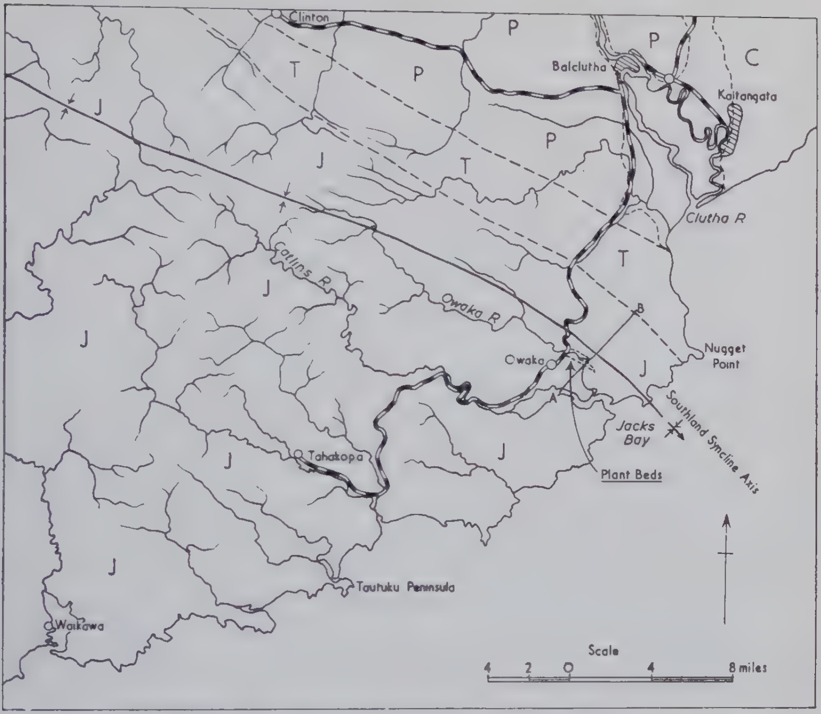

FIG. 1.—Map of South-East Otago—Southern Southland, showing location of Owaka Creek plant beds. Geology after Ongley (1939), Mackie (1935), with modifications. Palezoic (P), Triassic (T), Jurassic (J), and Cretaceous (C).

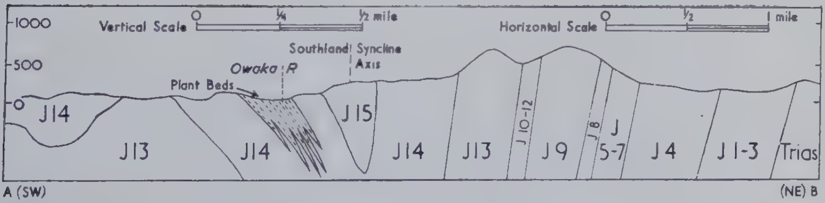

FIG. 2.—Mackie's section A–B (1935, Pl. 51) with position of Owaka Creek plant beds indicated. Sub-surface extent hypothetical.

Arber (1917, p. 11) tentatively assigned the flora to the Rhaetian or Lower Jurassic, but was inclined to favour Rhaetian because of the abundance of *Thinnfeldia*. Although he did not discuss the age of the Owaka Creek flora, Edwards (1934, p. 82) concluded that the various Jurassic floras of New Zealand closely resemble each other and are probably not older than Middle Jurassic. On the evidence of the plants, Mackie (p. 287) placed the J. 14 mudstones in the Lower Oolite (Bajocian). Marwick (1935, p. 27) tentatively attributed a Heterian (Callovian-Oxfordian) age to the Jacks Bay faunule. However, at that time the stratigraphical relationship of the Jacks Bay beds to the Owaka Creek plant-beds was unknown.

During 1955 and 1956, the author and others collected ammonites at Jacks Bay from the *H. haastiana* beds and the overlying mudstone. These have been examined by Dr W. J. Arkell, Sedgwick Museum, Cambridge, in conjunction with Dr J. H. Callomon, London. The ammonites are distorted and fragmentary, and none of them agrees satisfactorily with any known forms. Drs Arkell and Callomon consider the ammonites indicate a Lower to Middle Callovian age (Upper Middle Jurassic—Arkell, 1956, p. 10), with the best preserved (CE 1463, N.Z.G.S.) perhaps best matched with *Macrocephalites (Kamptokephalites) etheridgei* Spath (1928) from the Lower Callovian of the Strickland River, New Guinea.

The Owaka Creek flora is thus Lower to Middle Callovian or somewhat younger, and is therefore younger than Arber (Rhaetian to Lower Jurassic) and Mackie (Lower Oolite) suggested.

ACKNOWLEDGEMENTS

The author wishes to thank Dr C. A. Fleming and Mr A. R. Mutch, both of the Geological Survey of New Zealand, for their assistance during the preparation of this note. Dr H. Callomon and the late Dr W. J. Arkell kindly identified the ammonites.

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NOTE ON THE COMPRESSIONAL ANGLE BETWEEN INTERSECTING TRANSCURRENT CLOCKWISE AND ANTI-CLOCKWISE FAULTS

By G. J. LENSEN, New Zealand Geological Survey, Department of Scientific and Industrial Research

(Received for publication, 6 June 1958)

Summary

It is shown that the compressional angle between intersecting major transcurrent clockwise and anti-clockwise faults is acute in tensional, and obtuse in compressional regions.

INTRODUCTION

Anderson (1942, p. 14) postulated the angle between a transcurrent fault and the plane of maximum tangential stress to be less than 45°. The compressional angle γ between intersecting major transcurrent clockwise and anti-clockwise faults will therefore be acute. Wellman (1954) showed that some major transcurrent faults intersect at an obtuse angle.

The author (Lensen, 1958) suggests γ to be 90° exactly, in his classification of faults.

DISCUSSION

The following discussion is based on the assumption that reverse faulting prevails in compressional regions and normal faulting prevails in tensional regions.

In compressional regions the earth-crust is shortening and major faults with a normal character are not expected to occur, as such faults involve a lengthening of the earth-crust. Conversely, major reverse faulting will not occur in tensional regions as this type of faulting involves a shortening of the earth-crust. Major transcurrent faults in compressional regions can therefore be expected to have a reverse component, while in tensional regions a normal component can be expected.

The author (Lensen, 1958) has suggested that, for solely transcurrent faults, the compressional angle (γ) is 90°. The diagram (Fig. 1) shows the relation between the Principal Horizontal Stress and all types of faults. In this diagram, γ for transcurrent faults with reverse components (Cr and Ar, compressional regions) is obtuse, while γ for transcurrent faults with normal components (Cn and An, tensional regions) is acute.

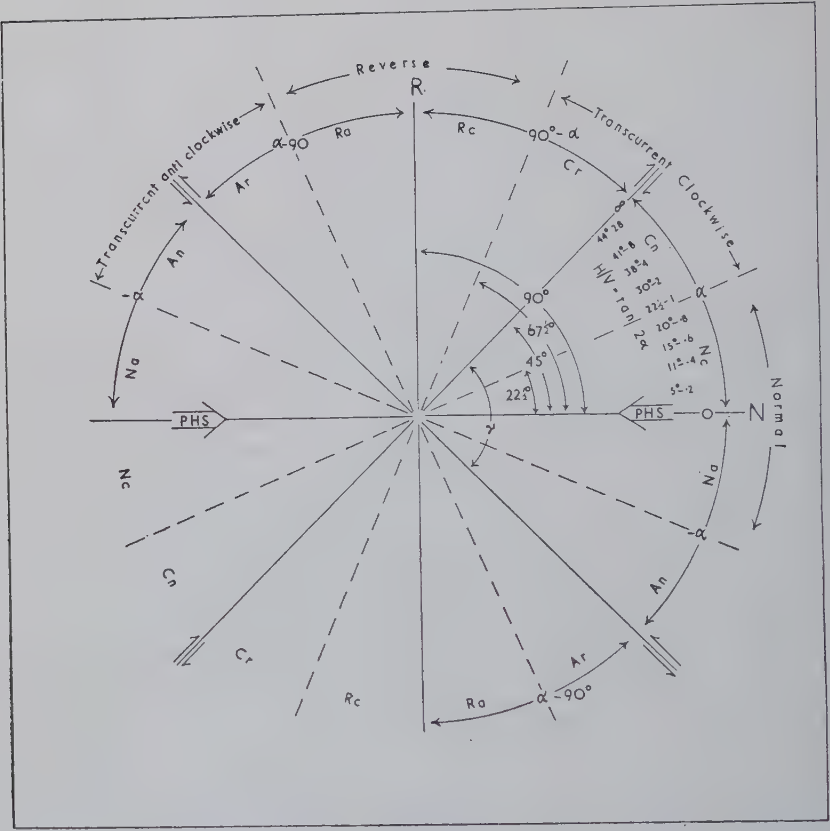

FIG. 1.—Relation between compressional angle (γ) and types of faults.

Once the stress conditions are taken into account, both Anderson's findings in England (tensional region) and Wellman's findings in New Zealand and California (compressional regions) fit this fault classification.

In recent seismological work Hodgson and others (Hodgson, 1955a, 1955b, 1955c, 1956, and 1957; Hodgson and Bremer, 1953; Hodgson and Cock, 1956a, b, and 1958; Hodgson and Milne, 1951; and Hodgson and Storey, 1954) in Canada, Hondo, and Masatsuka (1952) in Japan, Ritzema (1955) and others in Indonesia, and Keilis-Borok (1956) in Russia used and improved Byerly's method (1926) of analyzing earthquake data to find two possible fault-plane solutions for each earthquake. Scheidegger (1955) summarized part of this work in a table of fault-plane determinations.

This table is given below in abridged form (Table 1) and the compressional angles γ have been incorporated. The fault types are according to Scheidegger (*op. cit.*) where *s* stands for sinistral (anticlockwise), *d* for dextral (clockwise), *t* for tensional, and *p* for pressure features. Where a fault has undergone both vertical and horizontal displacement, Scheidegger tabulates the lateral sense of displacement first, irrespective of whether the transcurrent component, or the normal, or the reverse component is the dominant one.

TABLE 1.—Fault-plane Solution. (Mainly after Scheidegger, 1955.)

Ref. No.	Date	Epi-centre	Solution	Dip Direction	Compressional Angle	Fault type
1	7/3/1927	35·7N	a	N60E	90	*s*
		135·1E	b	N30W		*d*
2	10/12/1927	38·0N	a	N45W	90	*d*
		139·0E	b	N45E		*s*
3	21/5/1927	31·8N	a	N25E	90	*s*
		131·8E	b	N65W		*d*
4	22/3/1930	35·0N	a	N05W	90	*d*
		139·1E	b	N85E		*s*
5	16/10/1930	36·3N	a	N25W	90	*d*
		136·3E	b	N65E		*s*
6	25/11/1930	35·1N	a	N83W	90	*s*
		139·0E	b	N07E		*d*
7	21/12/1930	34·8N	a	N47E	90	*s*
		132·9E	b	N43W		*d*
8	9/1/1931	39·8N	a	S75E	180	*p*
		140·6E	b	N75W		*p*
9	20/2/1931	44·5N	a	S21E	90	*d*
		135·7N	b	N69E		*s*
10	21/4/1931	38·5N	a	N75E	90	*s*
		134·2E	b	N15W		*d*
11	2/6/1931	36·0N	a	N62E	90	*s*
		137·5E	b	N28W		*d*
12	16/8/1931	30·9N	a	N28E	97	*dp*
		104·2W	b	S55E		*sp*
13	21/9/1931	36·0N	a	N15E	90	*s*
		139·3E	b	N75W		*d*
14	2/11/1931	32·4N	t	N15E	90	*s*
		132·1E	b	N75W		*d*
15	3/11/1931	39·5N	a	N45E	90	*d*
		141·7E	b	N45W		*s*
16	4/4/1932	30·5N	a	S20E	90	*d*
		139·1E	b	N70E		*s*
17	25/7/1932	35·2N	a	S03E	67	*st*
		139·1E	b	N70W		*dt*
18	23/9/1932	44·7N	a	S02E	90	*d*
		139·0E	b	N88E		*s*
19	26/11/1932	42·4N	a	N65W	90	*d*
		142·3E	b	N25E		*s*
20	5/12/1932	33·7N	a	N90E	180	*p*
		137·0E	b	N90W		*p*
21	11/3/1933	26·5N	a	N60E	0	*t*
		140·5E	b	S60W		*t*
22	2/9/1933	30·3N	a	S46E	63	*dt*
		139·4E	b	N17E		*st*
23	21/9/1933	37·1N	a	N05W	90	*d*

Ref. No.	Date	Epi-centre	Solution	Dip Direction	Compressional Angle	Fault type
		137·0E	b	N85E		*s*
24	4/12/1933	46·4N	a	N75E	90	*s*
		144·3E	b	S14E		*d*
25	6/7/1934	41·4N	a	N50E	90	*dp*
		125·4W	b	S40E		*sp*
26	18/8/1934	35·7N	a	N40W	90	*d*
		137·0E	b	N50E		*s*
27	15/4/1935	36·2N	a	S14W	74	*st*
		137·1E	b	N60W		*dt*
28	31/5/1935	38·6N	a	N65E	89	*st*
		134·2E	b	S24E		*dt*
29	25/6/1936	32·5N	a	N90W	90	*s*
		137·9E	b	S00W		*d*
30	1/12/1936	30·7N	a	N79W	90	*s*
		129·0E	b	N11E		*d*
31	29/4/1937	45·7N	a	S02E	90	*d*
		137·3E	b	N88E		*s*
32	22/6/1937	64·7N	a	S36W	89	*dt*
		147·0W	b	S55E		*st*
33	11/8/1937	06·5S	a	N11E	55	*st*
		116·5E	b	S44E		*dt*
34	11/1/1938	33·7N	a	N10E	90	*d*
		135·2E	b	N80W		*s*
35	7/2/1938	36·3N	a	N24E	90	*s*
		139·2E	b	S66E		*d*
36	28/5/1938	43·6N	a	N45E	90	*s*
		144·3E	b	N45W		*d*
37	21/4/1939	47·6N	a	S36W	57	*dt*
		140·2E	b	S87E		*st*
38	1/5/1939	40·0N	a	N35W	90	*d*
		139·8E	b	N55E		*s*
39	22/9/1940	08·0N	a	N53E	41	*dt*
		124·0E	b	N86W		*st*
40	26/11/1940	36·5N	a	N80E	90	*d*
		139·5E	b	N10W		*s*
41	30/12/1940	34·2N	a	N50E	0	*t*
		136·8E	b	S50W		*t*
42	16/3/1941	38·5N	a	N68E	90	*d*
		012·0E	b	N22W		*s*
43	15/7/1941	36·7N	a	N34E	90	*s*
		138·2E	b	N56W		*d*
44	25/11/1941	37·3N	a	N87E	90	*s*
		019·0W	b	N03W		*d*
45	4/3/1943	35·6N	a	N73E	90	*s*
		137·2E	b	N17W		*d*
46	4/3/1943	35·6N	a	N23W	90	*d*
		134·2E	b	N67E		*s*
47	12/8/1943	37·3N	a	N38E	90	*s*
		139·8E	b	N52W		*d*
48	10/9/1943	35·5N	a	N22W	90	*d*
		134·2E	b	N68E		*s*
49	13/10/1943	36·8N	a	N18E	90	*d*
		138·2E	b	N72W		*s*
50	17/11/1943	33·0N	a	S00W	90	*d*
		138·0E	b	N90W		*s*
51	1/4/1946	53·5N	a	N25E	87	*dt*
		163·0W	b	N68W		*st*
52	23/6/1946	49·9N	a	N67E	24	*dt*
		124·9W	b	N89W		*st*

Ref. No.	Date	Epi-centre	Solution	Dip Direction	Compressional Angle	Fault type
53	4/11/1946	39·8N	a	N69W	0	*t*
		54·5E	b	S69E		*t*
54	10/11/1946	08·0S	a	N45E	100	*sp*
		078·0W	b	N55W		*dp*
55	18/2/1947	33·0N	a	S81W	90	*d*
		136·8E	b	N72W		*s*
56	16/10/1947	64·0N	a	N60E	0	*t*
		148·0W	b	S60W		*t*
57	28/6/1948	36·1N	a	N78E	90	*s*
		136·2E	b	N12W		*d*
58	29/6/1948	16·0S	a	N43W	91	*dp*
		172·9W	b	N48E		*sp*
59	8/9/1948	21·0S	a	S62E	93	*dp*
		174·2W	b	S31W		*sp*
60	30/12/1948	51·0N	a	N25E	59	*st*
		131·0W	b	S34E		*dt*
61	20/1/1949	35·6N	a	N85E	90	*s*
		134·6E	b	N05W		*d*
62	5/4/1949	43·0N	a	N23W	107	*dp*
		131·0E	b	N84E		*sp*
63	5/4/1949	42·0N	a	N22W	90	*d*
		131·0E	b	N68E		*s*
64	13/4/1949	47·0N	a	N41W	125	*sp*
		122·6W	b	S14W		*dp*
65	20/4/1949	38·0S	a	N53E	90	*d*
		072·5N	b	N37W		*s*
66	3/5/1949	49·0N	a	S84W	95	*dp*
		153·0E	b	N01W		*sp*
67	12/6/1949	27·0S	a	N90W	90	*d*
		064·0W	b	N00N		*s*
68	11/7/1949	34·0N	a	N73W	90	*s*
		132·5E	b	N17E		*d*
69	23/7/1949	18·5S	a	S50W	91	*sp*
		169·0E	b	S41E		*dp*
70	5/8/1949	01·0S	a	N08W	84	*st*
		078·0W	b	N88E		*dt*
71	22/8/1949	54·1N	a	N61E	93	*dp*
		132·6W	b	S26E		*sp*
72	3/11/1949	48·0N	a	N23E	88	*st*
		154·0E	b	S65E		*dt*
73	22/11/1949	29·0S	a	N40W	90	*dp*
		178·0W	b	N50E		*sp*
74	17/5/1950	21·0S	a	N86W	94	*dp*
		169·0S	b	N08E		*sp*
75	19/5/1950	20·5S	a	N58W	92	*dp*
		169·0E	b	N34E		*sp*
76	19/5/1950	20·5S	a	N88W	92	*dp*
		169·0E	b	N04E		*sp*
77	26/5/1950	20·2S	a	N80W	96	*dp*
		169·2E	b	N16E		*sp*
78	27/5/1950	20·0S	a	S67W	90	*st*
		168·0E	b	N23W		*dt*
79	28/5/1950	20·0S	a	N43W	90	*d*
		169·0S	b	N47E		*s*
80	21/6/1950	20·2S	a	N80W	94	*dp*
		169·5S	b	N14E		*sp*
81	24/6/1950	20·5S	a	S86W	92	*dp*
		169·5E	b	N02W		*sp*

Ref. No.	Date	Epi-centre	Solution	Dip Direction	Compressional Angle	Fault type
82	17/7/1950	20·5S	a	S60W	90	*dp*
		171·0S	b	N30W		*sp*
83	21/7/1950	15·5S	a	N19E	118	*dp*
		168·5S	b	S43E		*sp*
84	22/7/1950	14·0S	a	N57E	90	*sp*
		167·0S	b	N33W		*dp*
85	10/9/1950	15·5S	a	S84E	92	*sp*
		167·0E	b	N04E		*dp*
86	2/12/1950	18·2S	a	S46W	91	*sp*
		167·0E	b	S45E		*dp*
87	13/2/1951	15·0S	a	S58W	90	*dp*
		175·0W	b	N32W		*sp*
88	10/3/1951	15·3S	a	N49W	89	*st*
		167·5E	b	N42E		*dt*
89	23/3/1951	31·0S	a	N57W	88	*dt*
		180·0E	b	S31W		*st*
90	28/8/1951	27·0S	a	N42W	90	*st*
		178·0E	b	N48E		*dt*
91	25/2/1952	17·0S	a	N52W	90	*st*
		173·5W	b	N38E		*dt*
92	9/5/1952	06·5S	a	S52E	102	*sp*
		155·0E	b	N26E		*dp*
93	13/7/1952	18·5S	a	S74E	97	*sp*
		169·5E	b	N09E		*dp*
94	21/7/1952	35·0N	a	S40E	140	*sp*
		119·0W	b	N00W		*dp*
95	27/7/1952	20·5S	a	N73W	90	*dp*
		179·0W	b	N17E		*sp*
96	11/9/1952	29·0S	a	N57W	90	*s*
		177·0W	b	N33E		*d*
97	14/9/1935	18·5S	a	N29W	90	*st*
		178·5E	b	N61E		*dt*
98	29/9/1953	36·5S	a	S36E	90	*dp*
		177·0S	b	S54W		*st*
99	13/1/1954	49·0S	a	S46E	90	*sp*
		165·0E	b	S44W		*sp*

In compressional regions, as indicated by the fault types *sp*, *dp*, or *p*, the 24 reference numbers 8, 12, 20, 54, 58, 59, 62, 64, 66, 69, 71, 74, 75, 76, 77, 80, 81, 83, 86, 92, 93, and 94, all represent earthquakes in which the compressional angle is obtuse. In the extreme cases, Nos 8 and 20, the compressional angles are 180°, the fault type is solely *p* and the transcurrent components *s* and *d* have disappeared. The two possible faults are co-linear and differ only in the direction of the dip.

In tensional regions, as indicated by the fault types *st*, *dt*, or *t*, the 17 reference numbers 17, 22, 27, 28, 32, 33, 37, 39, 41, 51, 52, 53, 56, 60, 70, 88, and 89, all represent earthquakes in which the compressional angle is acute. In the extreme cases 21, 41, 53, and 56, the compressional angle is 0°, the fault type is solely *t* and the transcurrent components *s* and *d* have disappeared. The two possible faults are again co-linear and differ only in the direction of dip.

In 45 cases, the reference numbers 1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 13, 14, 15, 16, 18, 19, 23, 24, 26, 29, 30, 31, 34, 35, 36, 38, 40, 42, 43, 44, 45, 46, 47, 48, 49, 50, 55, 57, 61, 63, 65, 67, 68, 79, and 96, all represent earthquakes in which the compressional angle is 90° exactly, and in all cases the faulting is solely transcurrent and no tensional or compression features are observed.

In 12 cases, the reference numbers 25, 73, 78, 82, 84, 87, 90, 91, 95, 97, 98, and 99, the compressional angle is again 90°, the prevailing character of the faults is transcurrent, as the horizontal component of displacement is far in excess of the vertical component of displacement (see Scheidegger, 1955, p. 71-7) and because the H/V ratio (see Lensen, 1958) approaches infinity, the compressional angle is 90°.

All given fault-plane solutions fit the suggested rule, with the exception of reference number 72, but in checking the original publication (Hodgson and Storey, 1954, p. 62-3) it was found that the dip direction for solution *b* should read S65E instead of S65W, and, after incorporating this correction, No. 72 also fitted.

CONCLUSION

On theoretical grounds, supported by geological and seismological evidence, the following rule is proposed:

"The compressional angle between transcurrent clockwise and transcurrent anti-clockwise faults is acute in tensional regions and obtuse in compressional regions."

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NOTES ON VOLCANISM AND STRUCTURE IN FRANKLIN COUNTY

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Summary

The basaltic rocks of Franklin County, South Auckland, are divided into two formations, the Franklin Basalts and the Bombay Basalts. The age of the former is Mid-Pleistocene, younger than the Tyrrhenian sea-level of 110 ft, and older than the Monasterian sea-levels of 40 to 80 ft; the latter may be Late Pliocence to Early Pleistocene in age.

Faulting of Pleistocene age has been due mainly to collapse along pre-existing fractures, following expulsion of lava. Nevertheless, transcurrent faulting shows that some horizontal compression was present. The local principal horizontal stress direction is likely to have been north-north-east during and since the Miocene, but the main period of faulting ceased prior to volcanism.

INTRODUCTION

Several economic surveys have taken the author to scattered localities in Franklin County. Observations made on these surveys, together with published information, have led to the deductions concerning structure and volcanology presented in this paper. These deductions, however, represent only a superficial description of the geology of this interesting area.

The geology of the county is dominated by an uplifted block, bounded by the Drury* and Pokeno faults (Fig. 1b). This block is predominantly of Mesozoic rocks with minor areas of Tertiary and basalt†. It is flanked by the Manukau and Pokeno lowlands, which consist mainly of terrestrial pumiceous sediments and basaltic rocks of Pleistocene age. Small Tertiary inliers to the west and south (not mapped, as their boundaries are not accurately known), and Tertiary rocks in a 2,000 ft deep drill-holes near Karaka (Fig. 1b) show that the Drury and Pokeno faults have downthrows of 2,000 to 2,500 ft, and about 1,000 ft, respectively.

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*The name Drury replaces the rather clusmy nomenclature of Papakura-Drury used in the past.

†The boundaries east of Drury Fault are those of Bartrum and Branch (1936) adjusted since air photo interpretation. These authors missed an area of Tertiary to the north-east of eruptive centre 34. This area was mapped as such from air photos and later verified in the field. The boundary of the volcanic area is taken mainly from Day (1948).

N.Z. J. Geol. Geophys. 1 : 541-59.

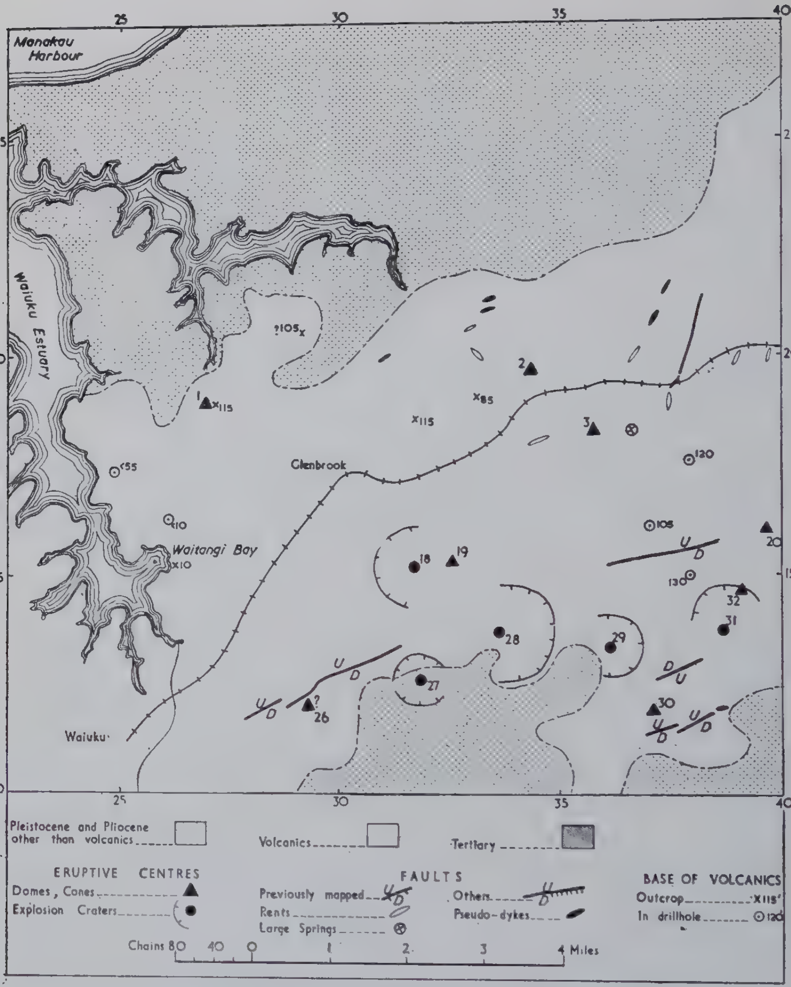

FIG. 1a.

FIG. 1.—Geological map showing the known distribution of volcanic centres and lines coincide with that of the Provisional 1 Mile Sheet N47. A small centres, see Appendix.

VOLCANISM

Although volcanism may have been more or less continuous, the evidence so far assembled suggests two main periods. The rocks of these are tentatively named the Franklin Basalts and the Bombay Basalts.

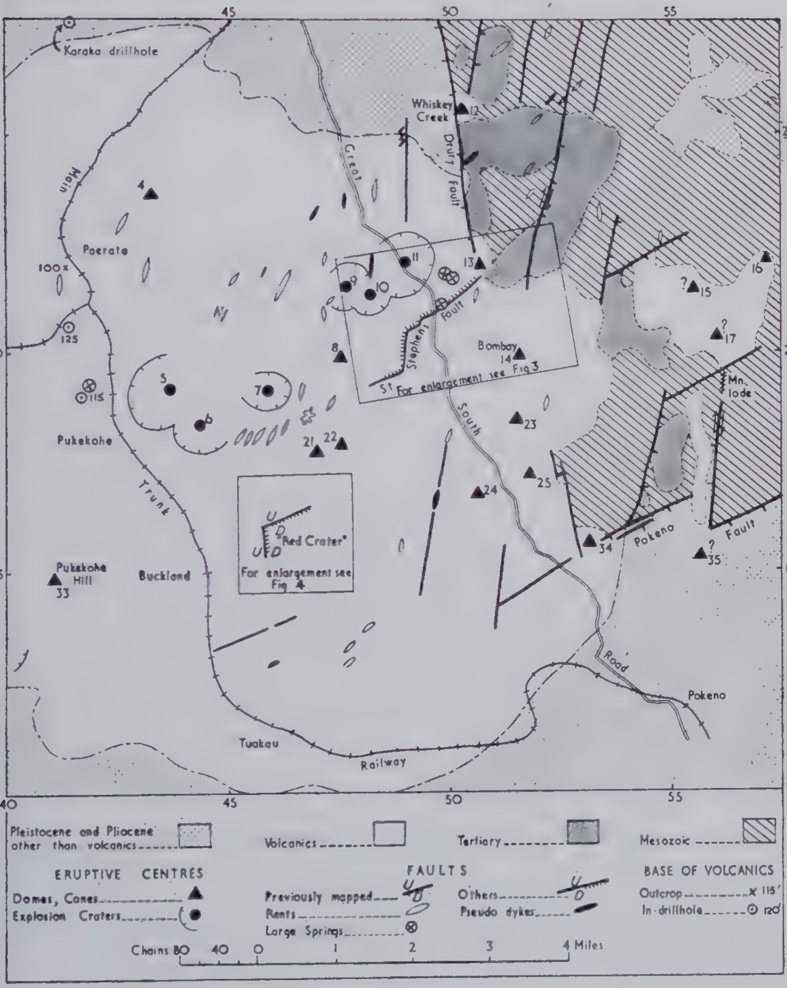

FIG. 1b.

faults within part of Franklin County. The southern boundary and grid portion of N48 is included to the east. For grid references to eruptive

Franklin Basalts

NAME

The Franklin Basalts include a flow on the eastern side of the Waiuku Estuary (see Fig. 1a) which has been named the Waitangi Bay Basalt by Gilbert (1921). Gilbert's (1921) Pakau Basalt, which lies immediately to the south of the area mapped in Fig. 1, is also probably part of the Franklin Basalts, but Gilbert obviously used both Waitangi Bay and Pakau to name individual flows when he wrote of the Pakau Basalt. "This lava-sheet and the associated basaltic breccia to the east are believed to be of the same age as the basaltic flows and breccias spread over a wide area to the north of the Waikato River and eastward of Waiuku." There is thus the choice of expanding one of Gilbert's terms or selecting a new name for a formation including the Waitangi Bay and Pakau basalts. As basalts occur near the better known Waitangi township within North Auckland, this name is best reserved for that area. In this paper the local name of Pakau is restricted to member rank, as Gilbert intended, and the district name of Franklin is used for a formation which groups together all the younger basalts and associated volcanic material. Although the full formation name should be strictly Franklin Volcanics or Franklin Formation, the lithological term "basalt" is more descriptive, and hence the name Franklin Basalts has been applied.

DESCRIPTION

The Franklin Basalts consist of basaltic flows, both dense and very vesicular, and fine and coarse basaltic tuffs. Where the latter surround explosion craters they are usually coarse, and contain boulders of Waitemata sediments and basalt. Although scoria has reputedly been encountered in drill-holes, very little is exposed at the surface.

Eruptions have formed domes, explosion craters, and occasional gently sloping cones. The gentle cones of Bombay Hill (Fig. 2) and Pukekohe Hill dominate the volcanic landscape and both rise 400 to

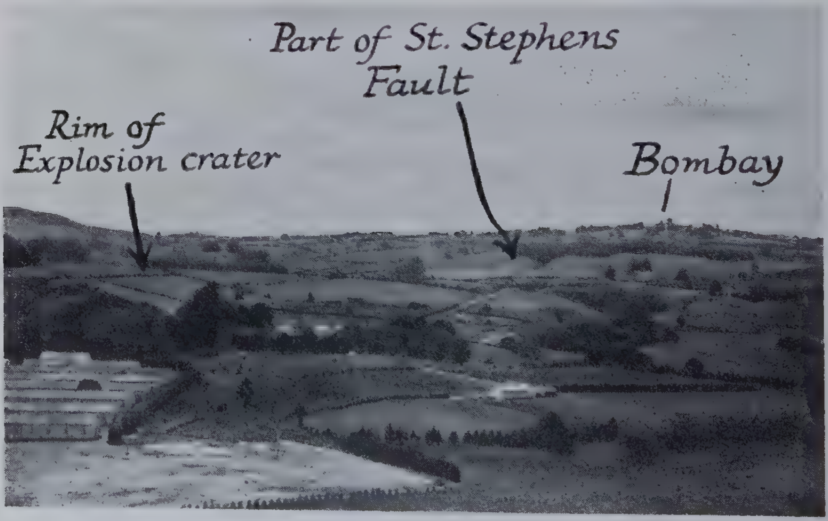

FIG. 2.—Taken from ridge at Martyns Redoubt.

500 ft above the adjacent lowlands. These cones are but little eroded, and this may be due to lack to run-off, for both are highly permeable. The lava flows on Pukekohe Hill are weathered to depths of 5 to 10 ft.

Undulating plains, at several levels above sea-level, have been formed either by fissure eruptions or by deposition of flows and volcanic debris on terrace remnants. The town of Pukekohe is built on one such level at 200 to 220 ft. It is characterized by numerous shallow hollows, which are several chains in width and have no surface outlet. Near Glenbrook, a widespread undulating surface at 170 to 180 ft above sea-level is underlain by 10 to 30 ft of tuffs, overlying 40 to 60 ft of basalt. With the exception of an area adjoining the Waiuku Estuary, at 9 of the 10 other known localities in the Glenbrook and Pukekohe areas (Fig. 1, a and b) the base of the Franklin Basalts is between 100 and 130 ft above sea-level, which suggests that the flat surfaces may be the result of deposition on widespread terrace remnants.

WIND DIRECTION

Both Pukekohe and Bombay hills are assymmetrical and steepest on their south-east side, which suggests that, while they were being formed, the prevailing winds were from the south-east, which would transport the bulk of the tuffs to the north-west.

AGE

The Franklin Basalts are underlain by pumice beds with interbedded peats. Samples of the latter (N47/536 to 539) contain no extinct plant microfossils and are presumed to be of post-lower Nukumaruan age (Mrs W. P. Tolley, pers. comm.).

More precise dating of the volcanism can be deduced by relating it to the eustatically controlled terraces of 40, 80, 110, and 230 ft above sea-level (Brothers, 1954). Drill-holes show that good terrace remnants at 200 to 220 ft, near the north-west fringe of the basalts, are not underlain by basalt, but are higher parts of the older landscape around which basalt has flowed. There are no known terraces cut at 110 to 130 ft within the volcanic area, and as the base of the Franklin Basalts in the western half is predominantly at this level, it may be assumed that volcanism postdates the 100 ft Tyrrhenian sea-level of Mid-Pleistocene age (see Brothers, 1954).

Terraces at 40 to 80 ft and on the outskirts of the volcanic region are not covered with ash, although at some outcrops they appear to be. This appearance may be due to the terrace being cut into older ash deposits or to sediments containing re-washed ash deposits. Many of the grey clays that directly underlie the surface of these terraces may also be derived from eroded ash, since they resemble the mother clays of the Rotokauri Soil Series, considered by Grange *et al.* (1939) to be derived from eroded Hamilton Ash.

In the nature of their weathering, the western basalt sheets are similar to the lavas of Pukekohe Hill, which in turn are in the same state of preservation as most of the domes and cones, including Bombay Hill. Hence the eruption of Franklin Basalts, which constituted the bulk of the volcanic activity, occurred between the Monasterian (40 to 80 ft) and Tyrrhenian (110 to 130 ft) sea-levels, i.e., about the time of the Penultimate glaciation.

Bombay Basalts

NAME

Older flows and tuffs crop out mainly in the eastern half of the volcanic terrain, and are here named the Bombay Basalts.

DESCRIPTION

No petrological studies have been made, nor have they been considered necessary to distinguish the Bombay Basalts from the Franklin Basalts, for they differ markedly in their state of preservation. The former are more deeply weathered and have no readily recognizable eruptive centres.

Many outcrops of coarse tuff have dips consistent with an explosion-crater origin, but the crater rims are not preserved, and more detailed fieldwork is needed to plot their centres. In many instances a small part of a Bombay explosion crater remains as a hill while the rest has been buried by the Franklin Basalts.

The only flow that can be definitely assigned to the Bombay Basalts surrounds Bombay Hill. It is especially well developed west of Bombay, where for two miles along the Great South Road and for a half mile to the west of this road, it underlies an undulating plain about 540 to 560 ft above sea-level. This plain is underlain by volcanic ash, but streams expose the older, 80 ft thick basalt sheet, with its top ranging from 480 to 500 ft above sea-level. It is above this plain that Bombay Hill, a volcano within the Franklin Basalts, has been built to 1,030 ft. Evidence for deducing that this cone is younger than the 560 ft surface includes: (a) the basalt below the plain is considerably more weathered, down to depths of at least 20 ft, and possibly was eroded prior to deposition of the covering ash; (b) erosion is greater on the plain, whose valleys cease at the foot of Bombay Hill; (c) there is a sudden change in hill slope where the Bombay Hill meets the 560 ft surface.

AGE

The Bombay Basalts are older than the Franklin Basalts but their precise age has not been determined. It is probably no more than a coincidence that the earliest Pleistocene terraces were formed at 550 ft (Brothers, 1954; Kear, 1957). Basaltic tuffs, perhaps derived from the Bombay Basalts, are found occasionally interbedded with the pumiceous sediments underlying the Franklin Basalts. Rare basalt pebbles also are found in nearby gravels of Waitotaran age. The Ngatutura Basalt of upper Waitotaran to lower Nukumaruan age at Kaawa (Kear, 1957) could well be a correlative.

EARTH FRACTURES

The presence of earth fractures in this area is shown by (1) surface displacement, (2) dykes and pseudo-dykes, and (3) rents.

Surface Displacement

The Drury and Pokeno faults have already been described (Laws, 1931; Bartrum & Branch, 1936; Battey, 1949). Fault planes near these faults have now been observed. The relation of dykes to the Drury Fault, described below, indicates that it is probably a reverse fault. Half a mile eastwards along the Pokeno Fault, crush zones in greywacke are vertical and strike at 052°. A mile from the southern end of the Drury Fault, a cross-fault is exposed in a small quarry, and strikes 060°, i.e., parallel to the Pokeno Fault. Here Mesozoic rocks are thrus over Tertiary sediments at angles between 30° and 70°.

Mead (1930) showed that the Wairoa Fault, which is east of and parallel to Drury Fault, strikes at 351°, is normal, and that its plane dips west at 80°.

The manganese lode shown on the eastern margin of Fig. 1, and another at N48/c690373, have developed in fault crush zones (Fyfe, 1933, MacPherson, 1941). Shutter ridges along the former show clockwise movement. They strike at 005° and 002° and have high dips of 65° to 80° but it is not known if the vertical components are reverse or normal.

ST. STEPHENS FAULT

A scarp striking in a general north-east direction to the south of St. Stephens College (Fig. 3) is interpreted as a fault scarp and the fault is named St. Stephens Fault. Several lines of evidence, no one of them itself conclusive, suggest that this scarp marks a fault. (A) the composite directions of the scarp parallel common fault directions. (B) the slope of the steep basaltic bluffs formed by erosion of the scarp appears too steep to be the termination of a flow (elsewhere in this region flows, unless eroded, thin out and merge into the surrounding landscape). (C) commencing at 380 ft above sea-level, on the down-throw side and at a distance of 10 chains from the fault, a bore at St. Stephens College (Fig. 3) passed through 50 ft of top soil and clay, 76 ft of volcanic rock, and 72 ft of volcanic ash and clay (Mr K. Hutchinson pers. comm.). Commencing at 500 ft above

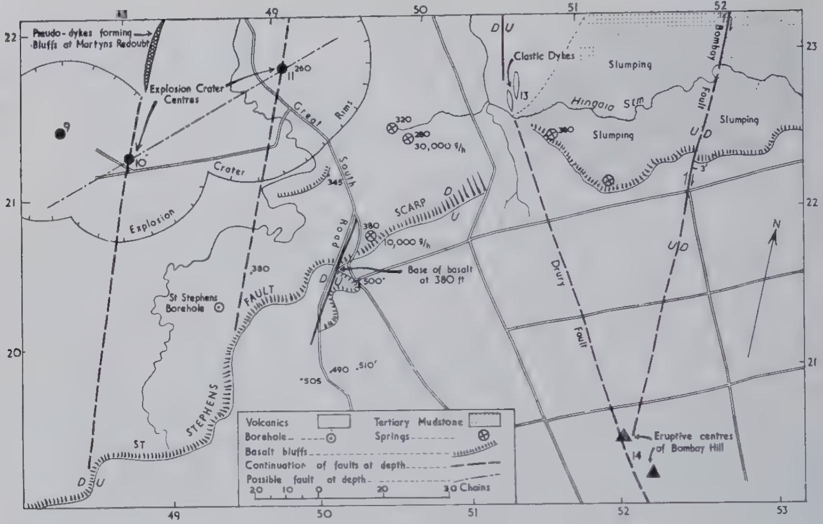

FIG. 3.—Detail of area outlined in Fig. 1b.

sea-level, the scarp itself shows, from the top, 30 ft of ash, 80 ft of basalt, and 10 ft of basaltic tuffs—a section almost identical to that in St. Stephens College drill-hole. However, it is possible that the basalt flow in St. Stephens College drill-hole might lie beneath that exposed in the scarp, and unfortunately there are no logs available from drill-holes south of the scarp to provide the required evidence. (D) that faulting could have taken place is shown by a small fault which cuts across St. Stephens Fault and runs parallel to the Great South Road (Fig. 3). This is shown topographicaly, and by a fault zone in which the uppermost ash is faulted against the basalt which is in turn faulted against the lower tuffs. (E) the scarp is 130 ft high close to Drury Fault. Westwards it diminishes and changes to a gentle slope for the last 30 to 40 chains. Farther west still a series of *en echelon* earthquake rents (Fig. 1) may have been caused by a lesser sub-surface movement along the continuation of St. Stephens Fault.

The occurrence of a similar scarp to the east of Drury Fault (Fig. 3) weakens the above evidence. Here a basalt flow, 75 to 100 ft thick and overlain by ash, rests on shales and mudstone of Oligocene age. It is unquestionably the same flow. However, here the scarp has been formed through erosion by the Hingaia Stream aided by slumping of the Oligocene mudstones. It is difficult to find a similar origin for St. Stephens Fault.

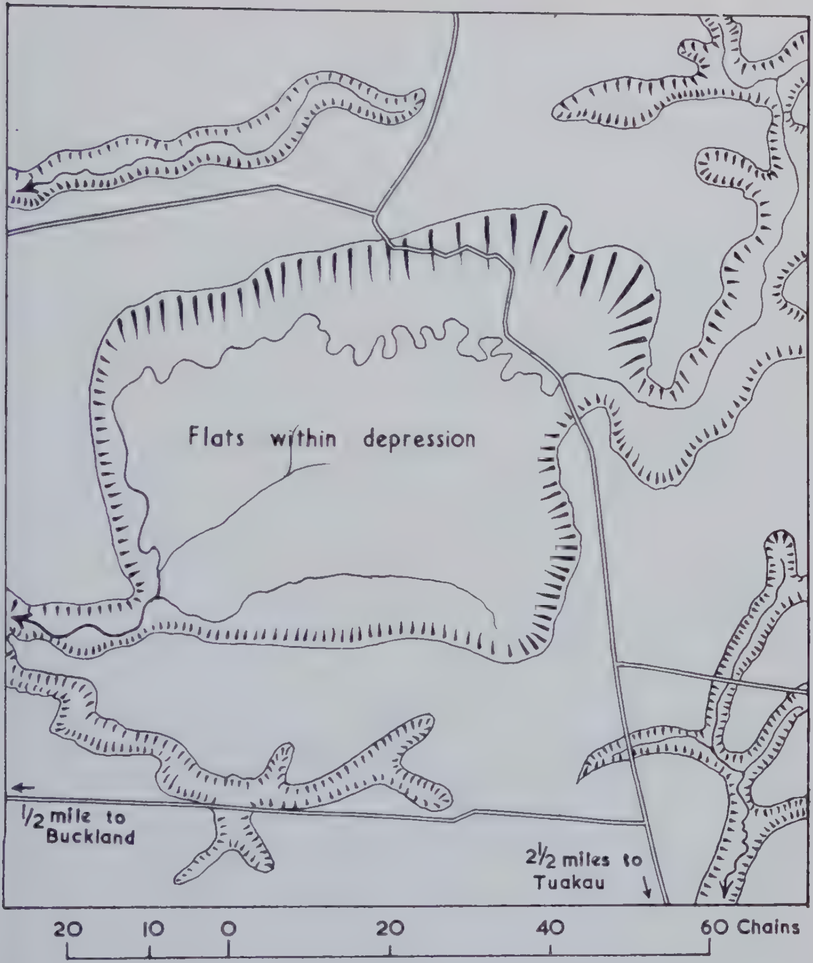

FIG. 4.—Buckland Red Crater depression (outlined in Fig. 1b). Drawn from vertically taken air photo to show relation to transverse stream and nearby streams.

BUCKLAND RED CRATER

One mile north-east of Buckland there is a rectangular depression known locally as the Red Crater (Figs 1b and 4). The surrounding rocks consist of tuffs with basalt exposed on the north side. The north and west walls are steeper than those east and south. A stream enters from a well defined valley to the east, meanders across the central flat where it is barely incised, then follows the northern wall, along which it flows westwards and thence southwards along the west wall, finally leaving the depression by the south-west corner, where it again has a well incised valley.

The preferred theory for the origin of the Buckland Red Crater is collapse. An alternative is that a flow has blocked the valley, but the abrupt widening of the valley has then still to be explained (Fig. 4).

BOMBAY FAULT

One mile north-east of, and striking towards Bombay Hill, a fault, here named the Bombay Fault, displaces bluffs in the Bombay Basalts, on the south side of Hingaia Stream, by a few feet vertically and 200 ft horizontally (Figs 3 and 5). Northward along it, similar horizontal shifts are shown by air photos. Among them is the displacement of the other valley side of the Hingaia Stream (Fig. 5). The southern continuation within the Bombay Basalts can be traced for 14 chains, the northern part being a well defined earthquake rent and the southern portion a sag (Fig. 5). Still farther south it disappears below the younger Franklin Basalts erupted from the Bombay Hill centre.

The Bombay Fault has a general strike of 007° (Fig. 3) and judging from the displacement of its trace as it crosses Hingaia Stream (Fig. 5), it is normal and has a fault-plane that dips at 70° to 80° eastwards.

FAULTS BASED ON AIR PHOTO INTERPRETATION

Other faults, shown in Fig. 1a and b, are interpreted as such from air photos but have not been investigated in the field. This interpretation is based either on straight bluffs, a mile or so in length, or on alignments of straight streams, eroded shatter zones, earthquake rents, or pseudo-dykes.

AGE OF FAULTING

Marwick (1948) summarized evidence for "the hypothesis that the Manukau depression was already formed" prior to the deposition of the Otahuhu faunule, i.e., the main period of faulting for this region is "Miocene, perhaps even well back in that period." Although much of the above described faulting is of Pleistocene age the author agrees with Marwick's hypothesis and interprets movements later than Miocene as being caused mainly by volcanism.

More exact dating of faulting within the Pleistocene is uncertain. St. Stephens Fault fractures basalt of early Pleistocene age. Bombay Fault fractures the same basalt and is covered with the later Franklin Basalts. The faulted depression of the Buckland Red Crater displaces basalt of unknown age. None of these faults can be proved younger than the Franklin Basalts, and could be associated with their extrusion, i.e., they could be of the same Mid-Pleistocene age.

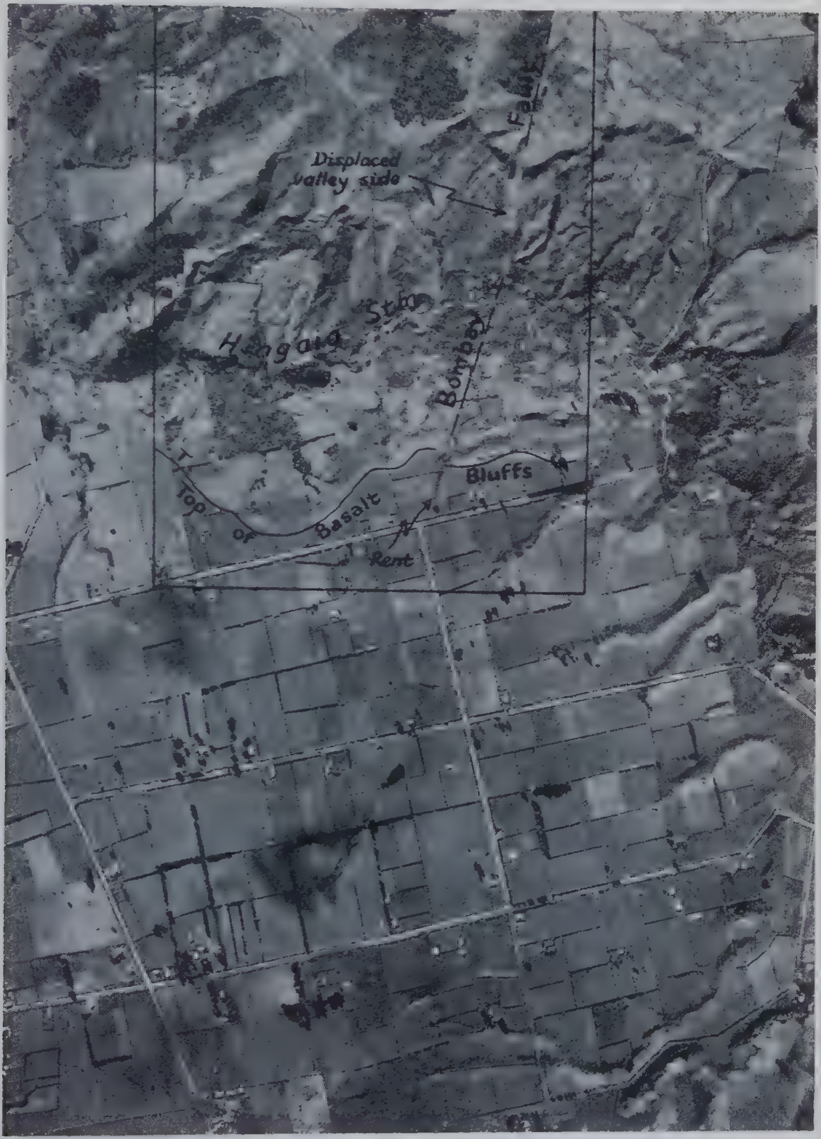

FIG. 5.—Vertical view of Bombay Fault. Reproduced through permission of the Surveyor-General, Lands and Survey Department of New Zealand.

Dykes and Pseudo-Dykes

Eruptive centre 13 (Fig. 3) lies along the Drury Fault and consists of a well eroded explosion crater plus columnar basalt which could

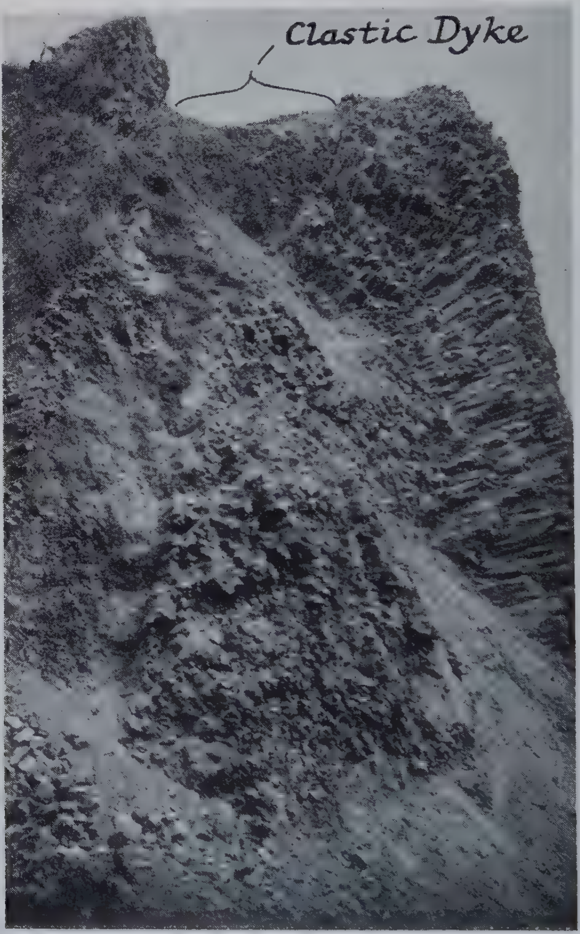

FIG. 6.—View south taken in a basalt quarry near eruptive centre 13, showing a 5 to 10 ft wide clastic dyke.

have been a sheet within the crater. The basalt has been intruded by a basaltic dyke that strikes at 348°, which is parallel to the average strike of the fault northwards from the centre. It dips eastwards at 67°. Between the western wall of the dyke and the country rock there is a clastic dyke, 2 to 3 ft wide, which is filled with volcanic ash (Fig. 6). Another clastic dyke, 5 to 10 ft wide (Fig. 7), strikes 340° as does the Drury Fault to the south, and dips 72° eastwards. As these dykes strike with the Drury Fault they are probably related, and their dips may suggest the dip of the fault-plane. If so, the Drury Fault is reverse.

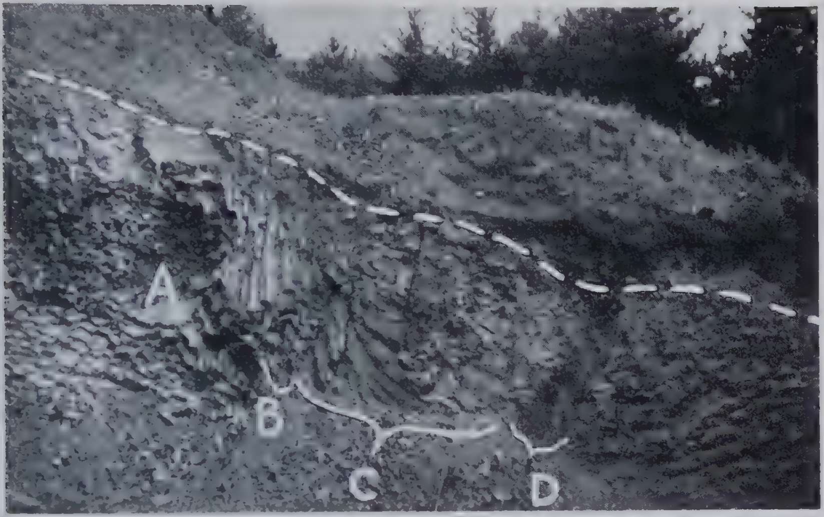

FIG. 7.—View south in same basalt quarry as Fig. 6. Lettering designates basalt, A; shattered contact, B; basaltic dyke, C; clastic dyke, D.

The name pseudo-dyke may be given to a hog-back ridge of once identical sediments left standing by selective erosion. Of those in Franklin County the most imposing is a straight ridge, 20 chains long, near Martyns Redoubt. Bluffs at the top of this ridge are nearly vertical for 50 ft. and trend 002°. They consist of well cemented, coarse basaltic tuffs and are capped by a slightly hog-backed ridge. The tuffs forming the pseudo-dyke are well cemented and unweathered. Identical, but soft and very weathered tuffs, make up the tuff rings of the nearby exposion craters. The latter tuffs can be no older than those of the pseudo-dyke, thus the protection of the pseudo-dyke from weathering is most likely to be due to cementation.

Rents

Some of the rents take the form of small hollows, or an alignment of small hollows with no outlet. The majority, however, occur as straight gash-like valleys, or, where they are on ridge tops, as elongated depressions. There are probably many more than the number mapped, for all transitions exist from normal valley forms to obvious rents.

These rents are probably not all of the same origin. Some are obviously true earthquake rents, as may be others that have been modified by erosion. Some may be the result of selective erosion along shatter zones. One star-like nest of rents, half mile north of eruptive centre 21 (Fig. 1b), could be the result of tension cracks produce by the doming action of an intruded laccolith.

DISCUSSION

Relationship of Pseudo-Dykes, Volcanism, and Faulting

Lava must be extruded up some weak or fractured zone within the earth's crust. The weakest spots will be chosen, and these are likely to be where two or more fracture zones meet. This is admirably demonstrated by four eruptive centres along the Drury Fault, which appear near the junctions of this and other faults (Fig. 1b). As the major fault directions are known for this area this thesis can be applied in areas where faults have been buried by undisturbed sediments. This is shown in Fig. 3, which also shows how pseudo-dykes may be related to buried fractures (see also Fig. 1b which shows that other pseudo-dykes are aligned with, or are parallel to, known faults). Pseudo-dykes are not themselves fractured, and must originally have had the same permeability as the once identical surrounding material. Thus it is difficult to postulate that their linear shape and cemented nature could be due to downward movement of ground-water. It is more likely that their cementation is due to volcanic emanations moving upward along fault zones.

Stress

The absence of any major compressional stress during volcanism in the area is shown by stable Pleistocene terrace levels common throughout the Manukau area and Northland peninsula. They have been correlated by Brothers (1954) with Pleistocene sea-levels, and are of greater age than most of the volcanism. Although volcanism itself may have some fundamental structural cause, extrusion may be the last phase of structural instability and the main stress may be vertical, an upward movement during extrusion followed by subsequent collapse*.

Almost certainly, only collapse could cause the rectangular depression of the Buckland Red Crater. Collapse along pre-existing fractures, is also the preferred explanation for the complex St. Stephens Fault. This fault increases in throw towards the Drury Fault, and near their junction clastic dykes strike with, and form continuations of, the Drury Fault. It is considered that these were formed at the same time, by collapse along the reverse Drury Fault, the resulting crevices being filled with ash and basaltic boulders from the surface. Bartrum and Branch (1936) also considered that movement along the Drury Fault occurred at a point 2 miles farther north, after the outpouring of basalt.

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*"Withdrawal, outflow, or blowing off of magma which has underlain considerable areas of surface seems to have been rather commonly the cause of collapse in which normal faults have been developed with the production of downward basins and complex grabens of irregular outline." (Cotton, 1944, p. 322.)

In Franklin County faults, of Pleistocene age either form continuations of, or lie parallel to, older fault trends. Thus, it would appear that when the main stress is vertical, new major fractures probably form by movement along older fractures. (This does not include all small earthquake rents or small tensional features such as may rise in directions radial to an eruptive centre). Also, if the main stress be vertical, volcanic extrusions may take place along any pre-existing fault, even possibly a reverse fault, e.g., the basalt dyke along the Drury Fault at eruptive centre 13.

Although the main stress during the Pleistocene may have been vertical, some horizontal stresses must have been present to cause transcurrent movement which is consistent with a P.H.S. (principal

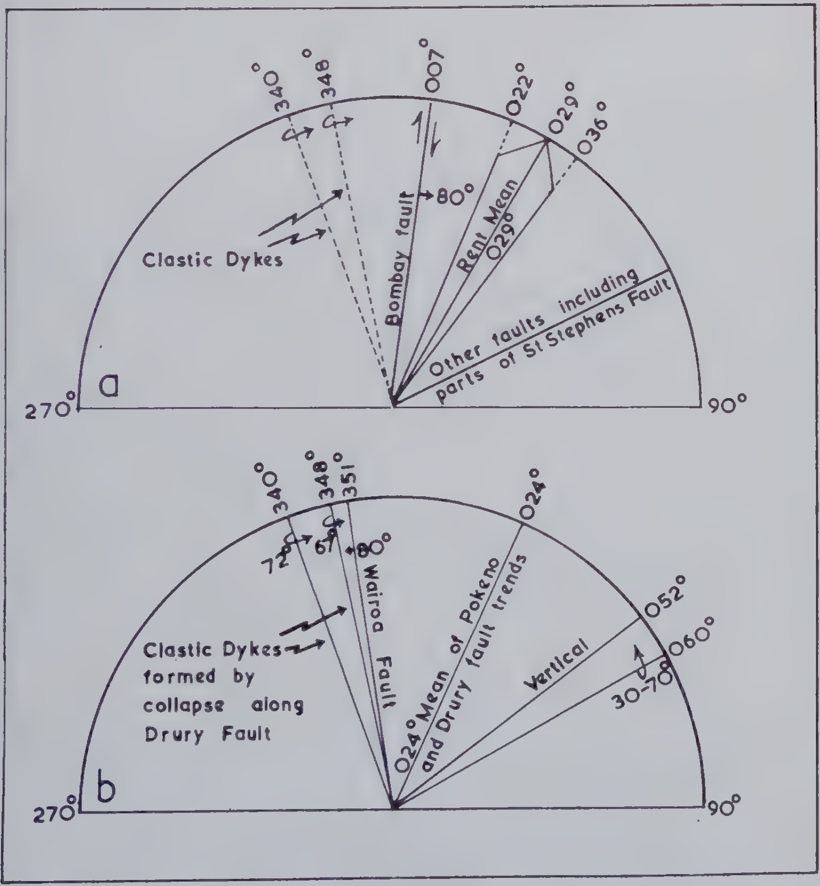

FIG. 8.—Fault patterns of (a), mid to late Pleistocene age and (b), probably Miocene age.

horizontal stress) striking within the north-east quarter. In the absence of folding it is difficult to be certain of its exact strike. However, apart from those that parallel the Bombay and Pokeno fault trends, the majority of rents strike between 022 and 036°, the mean being 029°. This is close to 024°, which is the strike halving the angle between the dominant Drury and Pokeno faults. Either of these directions, 024° or 029°, could be the local P.H.S. during the Pleistocene (Fig. 8a). The P.H.S. direction during the Miocene (Fig. 8b) was probably the same, but it should be noticed that faults at less than 40° to the P.H.S. have reverse components. These reverse movements may be due to the effects of gravity, like the development of low-angle thrusts along the Alpine Fault (Bowen, 1954).

Comparison With Other Stress Directions

Wellman (1954) described faulting in six localities within the north-west half of the North Island of New Zealand, where his greatest horizontal stress (P.H.S.) directions range from 035° to 057°. He concluded that "the stress pattern is relatively simple and uniform . . . and that it has not changed appreciably in direction since upper Miocene times." Of these six localities the P.H.S. direction at two (Waihi and Te Aroha) are based on a hypothesis that lodes have developed along faults of a purely normal character which are parallel to the P.H.S.; the P.H.S. direction at a third (Ngawha) is based on an extension of this hypothesis. However, Wellman also correlated the Buck Reef at Te Aroha, which strikes 006°, with one of the main directions of transcurrent faulting. This would suggest that veins, mineralized or otherwise, are able to form along any fault providing it has some tensional stress in its make-up. Wellman's suggestion that the stress pattern is relatively simple in the northern third of the North Island does not hold, but the P.H.S. directions for each of his six localities probably lies somewhere within the north-east quadrant, as it does for Franklin County.

ACKNOWLEDGEMENTS

Thanks are expressed to Mr A. C. Bettany, Engineer of Franklin County, whose knowledge of the County and interest in its geology greatly assisted the author. Much valuable information has also been obtained from drill-logs freely supplied by Mr G. Gilberd, Mr K. J. Hutchinson, and Mr L. H. West, all of whom are, or were, drillers in the County.

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APPENDIX

Localities and remarks on eruptive centres shown in Figs 1a and 1b.

Centre	Grid Ref.	Remarks
(1)	N47/272189	Very small dome underlain by more than 45 ft of basalt which thins to 12 ft in 5 chains.
(2)	N47/343197	Medium sized dome near Patumahoe (Day, 1948).

Centre	Grid Ref.	Remarks
(3)	N47/357183	Small dome (Day, 1948).
(4)	N47/432237	Possible dome (Day, 1948).
(5)	N47/437193	Explosion crater (Day, 1948).
(6)	N47/444184	Explosion crater.
(7)	N47/459192	A very fine example of an explosion crater known as Papach's crater. Tuffs on south side overlie pumice sands at 400 ft.
(8)	N47/475200	Medium sized dome.
(9)	N47/477216	Explosion crater.
(10)	N47/482214	Explosion crater.
(11)	N47/490222	Explosion crater surrounding Ravensthorpe Mental Hospital. A bore near the centre showed, 30 ft of ash, about 170 ft of basalt, then 40 ft of fine white pumice and ash.
(12)	N47/503257	See Bartrum and Branch (1936, p. 403).
(13)	N47/508222	"columnar lava . . . possibly the products of a small local eruption" (Bartrum and Branch, 1936). On the southern margin coarse tuffs dip south and southwest. The basalt could be an eroded filling of an eroded explosion crater.
(14)	N47/517201	Bombay Hill cone. At crest, two close knobs are aligned at 307°.
(15)	N48/557217	Possible dome (Bartrum and Branch, 1936).
(16)	N48/574225	Possible centre of eruption (Bartrum and Branch, 1936).
(17)	N48/560205	Same as for (16).
(18)	N47/317152	Explosion crater (Day, 1948).
(19)	N47/325153	Small dome almost cone shaped and well preserved.
(20)	N47/397161	Flat dome.
(21)	N47/469180	Same as for (20).
(22)	N47/474181	Same as for (20).
(23)	N47/517187	Dome.
(24)	N47/507168	Same as for (23).
(25)	N47/518173	Eroded dome, most likely source of flows abutting against southern extension of Drury Fault.
(26)	N47/293120	Possible dome.
(27)	N47/319126	Explosion crater.
(28)	N47/337138	Same as for (27).
(29)	N47/362134	Same as for (28).
(30)	N47/371120	Cone in good preservation.

Centre	Grid Ref.	Remarks
(31)	N47/387138	Approximate centre of explosion crater remnant.
(32)	N47/391147	Eroded small cone near Puni tennis courts.
(33)	N47/411149	Top to large cone of Pukekohe Hill.
(34)	N47/533160	Eroded basalt dome.
(35)	N48/555147	Possible cone of which shape is only evidence.

BOUGUER ANOMALY MAP OF NEW ZEALAND

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(Received for publication, 8 July 1958)

Summary

The Bouguer map of New Zealand exhibits two major negative gravity anomalies. The Rangitikei-Waiapu Anomaly, which intersects the axial ranges of the North Island, indicates a crustal downwarp which is not in isostatic equilibrium. This anomaly is closely parallel to the zone of intense seismicity, to the Taupo-White Island volcanic belt, to the Kaimanawa-Huiarau-Raukumara Ranges, to the thick Upper Pliocene sediments, and to the Hikurangi Trench; and it appears to be an expression of an active tectonic belt related to the Tonga-Kermadec-Hikurangi Trenches. The Rimutaka-Ruahine axial ranges are apparently not underlain by mountain roots.

The Alpine Anomaly in the South Island is considered to be the gravitational expression of the crustal roots of the Southern Alps and the mountains south-west of Blenheim; the magnitude of the anomaly suggests that this region is approximately in isostatic equilibrium.

Introduction

Since 1947 the Department of Scientific and Industrial Research has made about twelve thousand measurements of gravity throughout New Zealand. H. W. Robertson and R. A. Garrick made 19 measurements in 1947-48 (Cook, 1957) using the Cambridge pendulum apparatus. Subsequent observations have been made with a North American gravity meter for two purposes: firstly, to establish a primary network of gravity stations, and secondly, to investigate the geological structure of limited areas.

The Primary Gravity Network, comprising 234 stations in the North Island and 184 in the South Island, was established by the looping system (Nettleton, 1940), and the closure errors distributed by the least squares method of Gibson (1941). The stations were spaced about 25 km apart along the main roads, and give a fairly uniform density of coverage over the whole of the North Island and most of the South Island. This network was linked to the pendulum stations, enabling an accurate calibration of the gravity meter to be obtained, and absolute values (based on Cambridge = 981 265·0 mgal) to be assigned to all stations; it has also been used as the basis for all detailed surveys. From this integrated system of observations, it is now possible to deduce the broad pattern of the earth's gravitational field throughout New Zealand.

The present paper gives the preliminary results concerning the large-scale geological structure of New Zealand—a subject which is today evoking considerable attention from geologists and geophysicists.

BOUGUER ANOMALY MAP

The Bouguer anomalies have been computed from the observed values by applying free air, Bouguer, and terrain corrections (Hammer, 1939) and subtracting the theoretical value derived from the 1930 International Formula (e.g., Nettleton, 1940). The Bouguer and terrain corrections have been based on densities of the rocks above sea-level as found by laboratory measurement. Greywacke and schist basement rocks have a density of about 2·67 g/cm³, whereas the Tertiary sediments and acid volcanics, for example, have densities of 2·15 and 2·00 g/cm³ respectively; because of this difference, the actual rock densities have been used in preference to the single conventional value of 2·67 g/cm³.

The Bouguer anomaly map (Fig. 1), therefore, represents abnormalities in the distribution of mass below sea-level. Throughout the North Island and most of the South Island, the anomalies are produced mainly by the sediments and volcanic rocks overlying the basement, and by deep-seated variations in the thicknesses of the crustal layers.

In Fig. 1, contour lines have been drawn at 20 mgal intervals; where observational control is poor the inferred contours are shown as broken lines. The contours have been superimposed on a generalized geological map, adapted from the Geological Map of New Zealand (New Zealand Geological Survey, 1958).

DISCUSSION

The Bouguer anomaly map (Fig. 1) shows two very pronounced negative anomalies: the Rangitikei-Waiapu Anomaly in the North Island, and the Alpine Anomaly in the South Island. All other features, including the Auckland and Southland Anomalies, are relatively minor in comparison with them.

Rangitikei-Waiapu Anomaly

The Rangitikei-Waiapu Anomaly is greatest in the vicinity of Marton, cuts across the axial ranges extending from Wellington to Whakatane, and gradually decreases from Napier towards East Cape. The shape of the contour lines in the Rangitikei district around Marton, and the magnitude and shape of the contours in the northern part of the South Island, indicate that this anomaly reaches its maximum intensity on the coast near Marton, and decreases rapidly in a south-westerly direction. The gravitational effect of the thick Pliocene sediments near the —160 mgal contour line is estimated, from borehole information, to be approximately —40 mgal, leaving an anomaly of about —120 mgal to be ascribed to deep-seated causes. The corresponding isostatic anomaly is unlikely to be significantly different, as this is an area of coastal plains, rising to a height of about 300 metres over a distance of about 40 km.

A consideration of similar factors at other points along the axis of the anomaly, and of the general configuration of contour lines, shows that the Rangitikei-Waiapu Anomaly is predominantly of deep-seated origin. This view is supported by the presence of the following features which closely parallel the anomaly:

(1) Shallow-focus earthquakes, particularly in the Wellington-Napier-East Cape region; intermediate-depth earthquakes in the Marton-Taupo-White Island region; and at least one deep-focus earthquake in the New Plymouth area (Eiby, 1958).

(2) The active Taupo-White Island volcanic belt (Grange, 1937).

(3) The Kaimanawa, Huiarau, and Raukumara ranges, lying along the north-western flank of the anomaly from Napier to East Cape.

(4) Thick Upper Pliocene sediments in the Marton area (Fleming, 1953), and to the north-west of Napier (Dr J. T. Kingma, pers. comm.), whose thickness is greatest along the axis of the anomaly. Pliocene sediments also overlie the greywacke of the axial ranges where these are intersected by the axis of the anomaly (Kingma, 1957).

(5) The Hikurangi Trench, situated off the east coast of the North Island (Brodie and Hatherton, 1958).

This evidence suggests that since about mid-Tertiary time the principal tectonic activity in the North Island has been concentrated about a north-east trending crustal downwarp whose present axis coincides with the Rangitikei-Waiapu Anomaly. This active tectonic belt appears to be related to the Tongà-Kermadec-Hikurangi Trench system.

Other North Island Features

The Rimutaka-Ruahine ranges, which form the southern half of the axial ranges between Wellington and Whakatane, are a pronounced topographic feature, many peaks rising to 1,500 metres. The lack of any negative gravitational anomaly directly associated with these mountains indicates that they are not underlain by any crustal roots.

The Auckland Anomaly follows a north-westerly trend for 500 km. from the vicinity of Rotorua to North Cape; this axis accords with the geological evidence (Macpherson, 1946). The gravitational evidence, combined with the almost complete absence of earthquake epicentres in the Auckland-North Cape area, suggests that this is not a tectonically active region by comparison with that of the Rangitikei-Waiapu Anomaly. At its southern end, the Auckland Anomaly swings towards a southerly direction, and near Rotorua the contours are

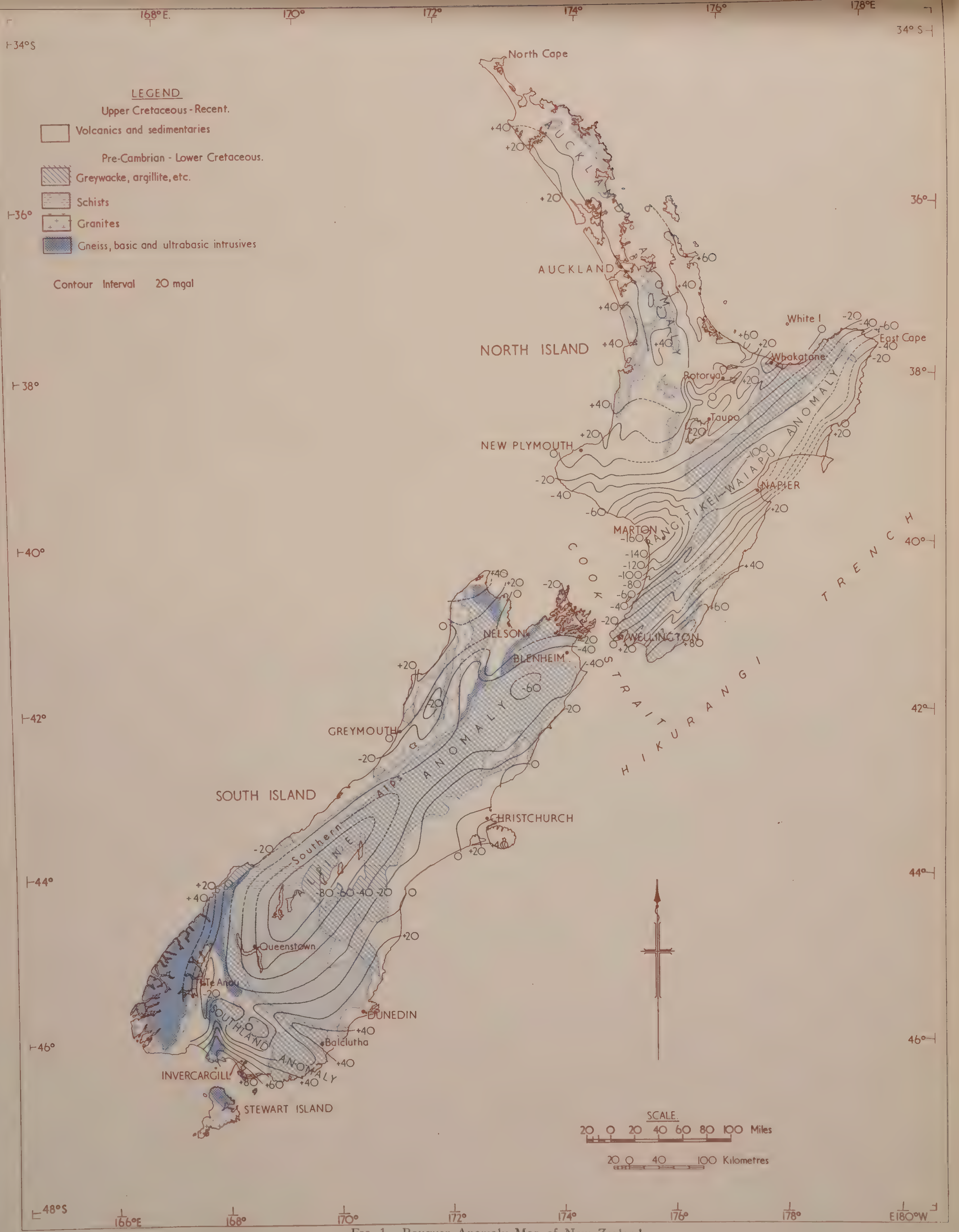

Fig. 1.—Bouguer Anomaly Map of New Zealand.

complicated by the influence of the younger north-east trending fault system of the Taupo-White Island volcanic belt.

Alpine Anomaly

The Alpine Anomaly differs notably in character from the Rangitikei-Waiapu Anomaly, since it is obviously directly related to the Southern Alps and the mountains south-west of Blenheim. The exposure of basement rocks over most of the area of the intense negative anomaly, and the general configuration of the contour lines, make it clear that this anomaly is of deep-seated crustal origin. The axis of the anomaly is, however, offset to the east of the crest of the mountain ranges. In the northern area south-west of Blenheim the offset is very slight; in the central area between Greymouth and Christchurch the offset is approximately 20 km.; whereas in the southern area of maximum negative anomaly north-east of Queenstown, the offset is about 40 km. In the northern and central areas the offset is reduced to zero by considering the elevation at any point to be the average elevation within a radius of 40 km. of the point, and the shapes of both the averaged topographic profile and the Bouguer anomaly profile become almost identical. This result is not surprising, since the Southern Alps are much steeper on the north-western than on the south-eastern side. In the southern area, however, the topography must be averaged over a radius of about 80 km. to bring the peaks of the topographic and anomaly profiles into coincidence; even then the shapes of the two profiles differ considerably. It would therefore appear that only in the southern part of the Alpine Anomaly is the deep-seated crustal downwarp likely to be offset from the generalized surface topography.

Southland Anomaly

The axis of the Southland Anomaly coincides with the axis of the Southland Syncline (Wellman, 1956); and the south-western margin appears to be related to the igneous intrusions along the coast near Invercargill and in the Longwood-Takitimu Ranges south of Te Anau.

CONCLUSIONS

New Zealand's two pronounced negative Bouguer anomalies—the Rangitikei-Waiapu Anomaly in the North Island, and the Alpine Anomaly in the South Island—are considered to be the gravitational expressions of two major crustal downwarps. The downwarp expressed by the Rangitikei-Waiapu Anomaly is an active and unstable tectonic feature, particularly in its south-western half; the other, expressed by the Alpine Anomaly, forms the subcrustal root of the South Island mountain system, which appears to be approximately in isostatic equilibrium.

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MEASUREMENT OF COMPRESSION AND TENSION: SOME APPLICATIONS

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(Received for publication, 18 March 1958)

Summary

Stress can be equated to vertical and horizontal fault displacements. Plotted on a map of New Zealand, the pattern of isallo-stress lines corresponds with that of Bouguer gravity anomalies. The regions of tension correspond with those of large negative gravity anomaly, while the compressional regions correspond with those of small negative and of positive gravity anomalies.

INTRODUCTION

In compressional regions reverse and transcurrent-reverse faulting and in tensional regions normal and transcurrent-normal faulting are dominant.

The writer (Lensen, 1958, a and b) demonstrated that the angle between solely transcurrent clockwise and anti-clockwise faults is 90°, and that in compressional regions the compressional angle between transcurrent clockwise and anti-clockwise faults is obtuse, while in tensional regions this compressional angle is acute.

THEORY

Faults that are entirely transcurrent clockwise and anti-clockwise intersect at right-angles. Any increase of the compressional angle produces transcurrent faults with reverse components. As the compressional angle γ increases the reverse component increases, and eventually becomes the dominant characteristic. The transcurrent component becomes infinitely small as the angle approaches 180°, and originally transcurrent faults become co-linear reverse faults (Fig. 1).

Similarly, when γ decreases the transcurrent faults have a normal component which, with further decreases in γ, becomes the dominant characteristic, and originally transcurrent faults become co-linear normal faults when γ becomes zero.

The amount by which γ deviates from 90° is here called the deviation angle, 2ϵ, which is positive for $\gamma > 90°$, and negative for $\gamma < 90°$.

It has been shown (Lensen, 1958a) that

$$H/V = \tan 2\alpha \qquad \text{............ (1)}$$

where H and V are the horizontal and vertical fault displacements respectively, and where α or its complement is the angle between a fault and the Principal Horizontal Stress.

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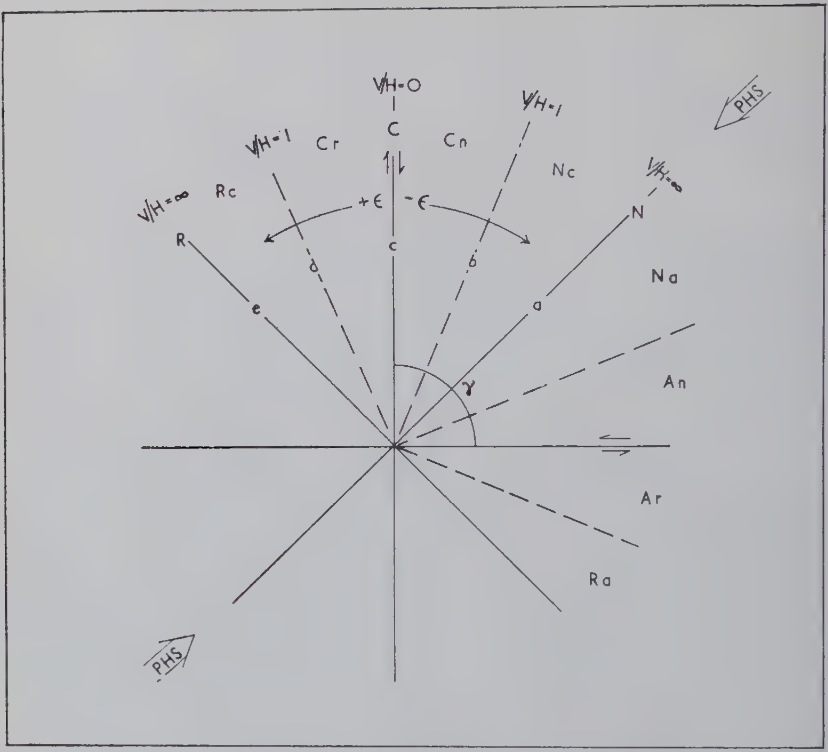

FIG. 1.—Showing the change in compressional angle with change in character of the faults.

The ratio of vertical to horizontal displacement (V/H) changes with the deviation angle as tabulated below:

	Compressional Angle (γ)	Deviation Angle (2ϵ)	V/H
(a)	0°	— 90°	∞
(b)	45°	— 45°	1
(c)	90°	0°	0
(d)	135°	45°	1
(e)	180°	90°	∞

The equation $V/H = \tan 2\epsilon$ ………… (2) holds.

Substituting for V/H from (1)

$$\tan 2\epsilon = \cot 2a \qquad \text{…………} \ (3)$$

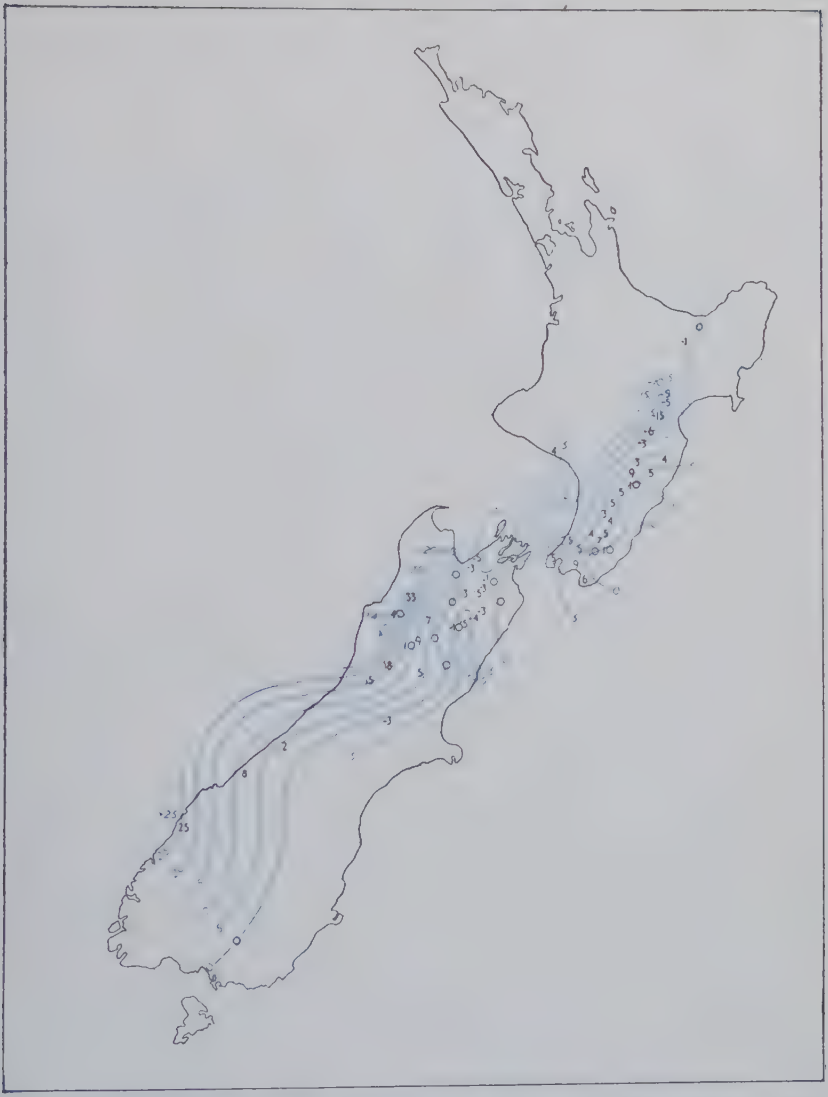

FIG. 2.—Showing the regional isallo-stress pattern for New Zealand. Note: The isallo-stress value "4" on the West Coast of the North Island should read "— 4".

In practice this means that ϵ—half the deviation angle—equals the Principle Horizontal Stress angle minus 45°, and any P.H.S. angle less than 45° indicates tension by that amount $(-\epsilon)$, while any

P.H.S. angle greater than 45° indicates compression by the amount $(+\epsilon)$.

APPLICATIONS

(1) New Zealand is part of the Circum-Pacific Mobile Belt and, as such, is dissected by several active major transcurrent faults. In both the North and South islands most displacements observed have taken place since Last Glaciation; movements during earlier Glacial epochs have generally been obliterated by erosion.

In the South Island recent vertical and lateral displacements have been measured by Wellman (1953). In the North Island numerous displacements have been measured by the writer, as part of a project still in progress.

The ϵ values obtained from the post-glacial data have been plotted in Fig. 2 and from these values it is possible to draw a regional isallo* stress pattern which shows regions of compression and tension. The isallo stress can vary from -45 to $+45$ degree units. The isallo-stress lines are independent of the strike of the faults indicating the Principal Horizontal Stress angles.

The map (Fig. 2) shows a remarkable correspondence with the gravity anomaly map (Robertson and Reilly, 1958) as shown in Fig. 3. The tensional areas correspond with the areas of large negative Bouguer anomalies, while the compressional regions coincide with small negative and positive Bouguer anomalies.

(2) The ϵ values define the character of the major faults and only those faults corresponding with these ϵ values can be present: i.e., in a tensional region with $\epsilon = -10°$ (P.H.S. angle $= \pm 35°$) only transcurrent clockwise and anti-clockwise faults with normal components, whose H/V ratios are $\pm 2{\cdot}7$, are possible. This confirms Wellman's assumption (1954) that the P.H.S. direction coincides with the bisector of the compressional angle between transcurrent clockwise and anti-clockwise faults.

(3) Fault plane studies by Hodgson (1957) based on first arrivals, and summarized by Scheidegger (1955), resolve fault movement into horizontal and vertical components. It is, therefore, possible to draw isallo-stress maps, based on seismic data, showing regions under compression and tension. Unfortunately, not enough earthquakes have yet been studied to arrive at a reasonably dense pattern.

In some places the magnitude and sign of the ϵ values change with depth, and when sufficient earthquakes have been studied it should be possible to draw isallo-stress maps at selected depths, thereby providing an additional method in the study of sub-crustal stress.

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*The term "isallo" is taken from meteorology, where it is used for second-order phenomena, e.g., change in barometric pressure.

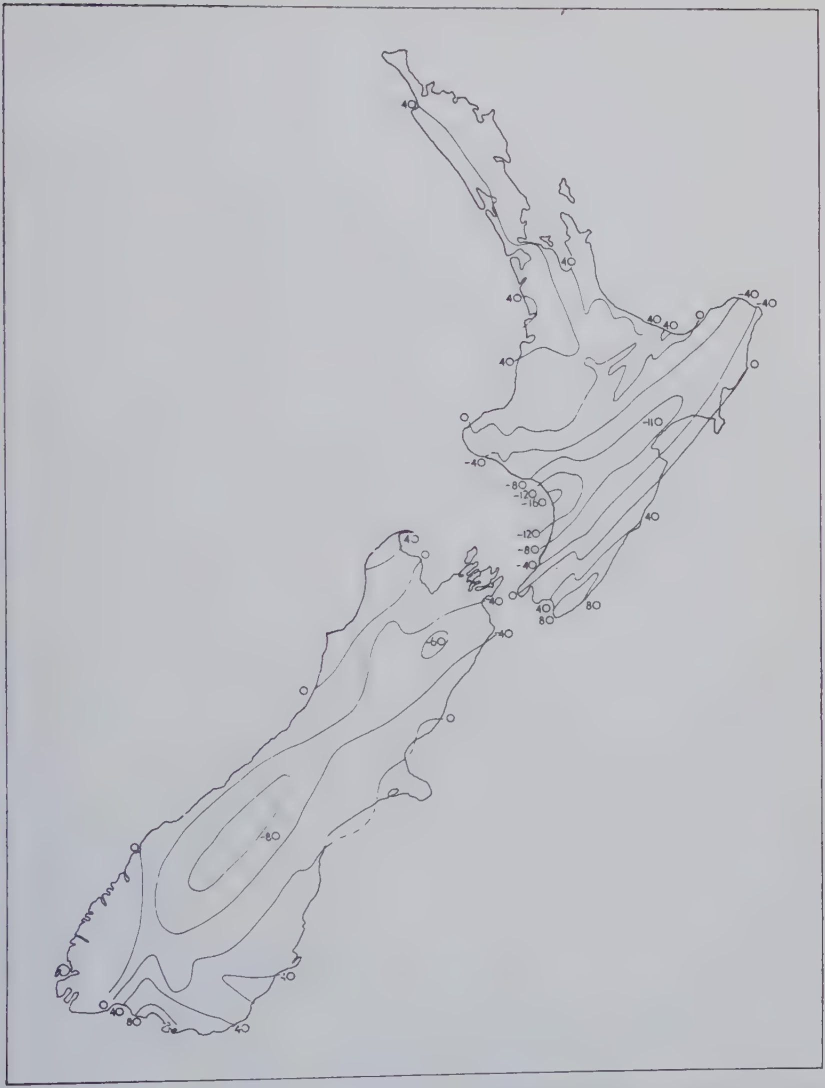

FIG. 3.—Showing Bouguer anomaly map (after Robertson and Reilly, 1958).

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A RADIOCARBON DATE FOR PENGUIN COLONIZATION OF CAPE HALLETT, ANTARCTICA

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Summary

During maxima of ice advances in the Last Glaciation, 10,000 to 30,000 years ago, the Ross Sea was filled by ice, so penguin colonization of shoreline breeding sites must have occurred since that time. The age of a frozen Adèlie penguin body from the base of an accumulation of penguin bodies and guano at the Cape Hallett rookery has been determined by the radiocarbon method as 1,210 ± 70 years. The rookery was probably colonized between about 400 and 700 A.D., at approximately the same time as a Northern Hemisphere warm period that stimulated a Viking expansion. There is no sign that it was temporarily abandoned at the time of a Northern Hemisphere cold period between 1650 and 1750 A.D.

INTRODUCTION

That glaciers draining from Antarctica were formerly much thicker, and projected further into the Ross Sea, has long been known from the evidence of high-level moraines, and of erratics perched on the sides of Quaternary coastal volcanoes several hundreds of feet and more above present sea-level (David and Priestley, 1914; Taylor, 1914). Additional topographic evidence was obtained by members of the New Zealand Geological Survey Antarctic Expedition which worked in the Cape Hallett district in northern Victoria Land in the summer of 1957-58.

If the Quaternary history of the continent was similar to that of other regions, there were probably several major "glaciations" separated by long "interglacials". Numerous radiocarbon dates from many parts of the world indicate that the main phases of the Last Glaciation occurred between about 10,000 and 30,000 years ago. In Antarctica the last major ice advance possibly occurred during the same time, but there is a theory that Antarctic land ice advances are not in phase with those of temperate and Arctic regions, even though the area and thickness of sea-ice almost certainly fluctuates in phase with the cold periods of temperate regions.

In any case, in the Ross Sea region there was at least one major ice advance, probably in the Late Quaternary, and there is evidence that the present Ross Sea was filled by piedmont glaciers, and probably also by an ice shelf which might have extended even as far north as Scott Island.

N.Z. J. Geol. Geophys. 1 ; 571-6.

When the New Zealand Geological Survey party at Cape Hallett had gained an understanding of the glacial history outlined above, it became clear that colonization by penguins of their nesting areas around the shores of the Ross Sea must have occurred since the Late Quaternary, and possibly within the last few thousand years, that is, well within the range of radiocarbon dating.

LOCATION OF SAMPLE AND AGE

Cape Hallett (72° 18′ 50″ S, 170° 12′ 30″ E) is a 1,000 ft cliff of basalt flows at the southern entrance to Moubray Bay. From the cape,

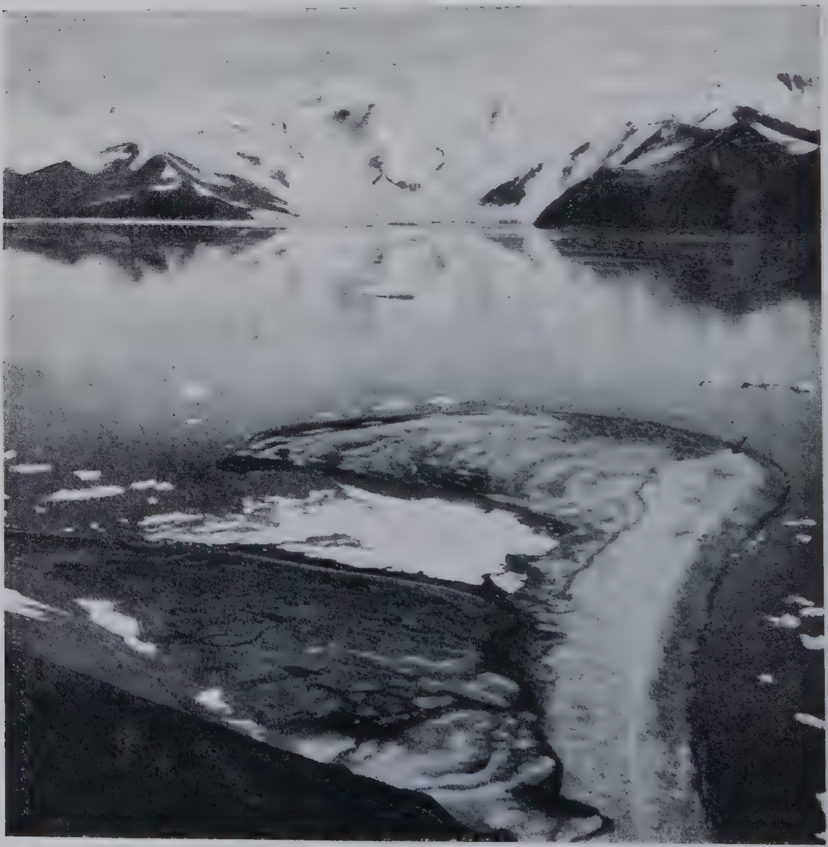

FIG. 1.—Seabee Spit from the cliffs of Cape Hallett in early February. The Adèlie penguin rookery occupies the area stained greyish white by guano, and Hallett Station is built on the darker area at the far end of the spit. The arrow shows the location of the radiocarbon sample. The three bergs beyond the arrow are stranded on an underwater extension of the spit. The highest background peak is Mt. Lloyd (10,650 ft).

Photo: A. J. Heine

a hooked bay-mouth bar, called Seabee Spit, extends for half a mile into the bay (Fig. 1) and the behaviour of stranded bergs shows that it continues under water for about another half a mile. The spit is an extension from a slightly earlier, roughly triangular beach, on the leeward side of the cape, and there is no evidence that it has grown on top of an older moraine. Most of the initial beach is occupied by nesting skuas, but the remainder of the beach and the spit (greyish-white, guano-stained areas in Fig. 1) are occupied between late October and late February by nesting Adèlie penguins. Snap estimates of the penguin population have ranged between 70,000 and 200,000 birds, the lower figure probably being nearer the mark. They live, to the extent that population pressure will allow, on the crests of hummocks on the main spit and on the curvilinear beach ridges that mark successive stages in the growth of the hook, but the whole surface of the nesting area is covered by a variable thickness of guano, the bodies of penguins and their chicks, and pebbles used for nests.

Near the western end of the spit on its northern side (see arrow in Fig. 1) a cut was made by a bulldozer through part of the main beach ridge, exposing 1 ft 3 in. of pebbles, guano, flattened hard permanently frozen bodiees of penguins, and the general debris of penguin occupation overlying 2 ft and more of clean beach gravel without organic remains. The penguin bodies are dry, and flattened to less than an inch in thickness. One of them was taken from the base of the layer of penguin accumulation, and its age determined by the ^{14}C method at the Nuclear Sciences Division of D.S.I.R. is 1210 ± 70 years (Sample R384, 1958).

DISCUSSION

The penguin lived about 750 A.D., and penguin debris has accumulated above it at the low rate of a little over one inch per hundred years. It is possible that neighbouring bodies at the base of the layer of penguin accumulation could differ in age by 200 years or more. That is, another penguin from the base of the deposit could have lived about 550 A.D. or earlier, and it was not necessarily one of the first colonizers. The colony might have started at some other point on the spit and, although there are no data concerning the rate of growth of an Adèlie penguin colony, it seems possible that by natural growth and immigration it could have spread over the spit within a hundred years or less if conditions were favourable. Penguins probably prefer nesting sites as close to the shore as possible because they are thus closer to a food supply, and because birds moving to and from nests farther inshore are pecked and harried by the ranks of birds closer to the shore. The sample site is very close to the shore and it is likely, therefore, that it would be occupied fairly early in the history of the colony. To sum up, it seems that the Cape Hallett penguin colony was established at some time between about 400 A.D. and about 750 A.D.

At several Adèlie penguin rookeries in the Ross Sea the birds must walk for miles across sea-ice to get to their nesting sites early in the summer season, and for the first month or longer must continue to walk considerable distances for feeding in pools and leads among the pack ice. However, when the chicks are growing rapidly later in the season the sea-ice near the rookeries breaks up, and feeding is possible close to the nests. It seems essential that this should happen for the chicks to get enough food to survive. At Cape Hallett until 24 December 1957 streams of birds could be seen walking in the direction of the Ross Sea to beyond the limit of vision through field glasses, that is for at least several miles, at a time when some eggs were still hatching. At the same time many birds were walking to a lead that extended like a giant tide-crack along the coast on the east side of Hallett Peninsula. From 24 December to early January pools opened in the ice within half a mile of the spit and birds were thickly clustered around them, but other birds were still walking seawards beyond the limits of vision. At this time, and earlier, scores of birds were noticed also in the vicinity of tide-cracks and slots in the sea-ice, at the head of Hallett Bay eight miles south of the station in the opposite direction from the open sea, and around tide-cracks along the western shore of Moubray Bay, but it is not certain that those birds were breeding. They had, in any case, walked there from the sea, and appeared to do little if any feeding. From 6 January onwards the sea-ice had broken up sufficiently for surf to break on the shore of Seabee Spit and all the birds could walk directly from the colony into the open sea. These observations may be used in consideration of climatic changes, or, more directly, changes in summer sea-ice cover since the establishment of the Hallett penguin rookery.

The thin layer of penguin debris in the cut was exposed horizontally for several feet and, though it would be difficult to detect, there was no sign of a break that would indicate that at some stage the breeding site had been abandoned and later re-occupied. At present the colony is nearly as large as it has ever been judging from the distribution of nests, guano, and birds, but all the available space is not used. The large area occupied by skuas could be taken over by penguins, which could also spread up the lower slopes of the cliffs as they have done at the Possession Islands and Cape Adare. The penguins are therefore living in conditions that are between marginal and optimum. There could be several important controls on the size of the rookery, including population pressure at other breeding sites, and changes in the abundance of penguin food, but the most important of them is probably the behaviour of the sea-ice. The colony would be extinguished or abandoned if the sea-ice did not break up fairly early in the life of the chicks. That in the last 1,200 years the sea-ice behaviour has not been more favourable than at present is shown by the fact that guano and abandoned nests do not occur much beyond the present limits of the colony, and that it has not been much less favourable than at present is suggested by the apparent lack of a break in the section through the penguin debris. This means that there have been only limited fluctuations in summer air and sea temperatures at Moubray Bay over the last 1,200 years, that is, since about 750 A.D. It is known from historical records and studies of glacier oscillations (Ahlmann, 1948; Flint, 1957) that in the Northern Hemisphere there were glacial maxima indicating colder conditions in periods centred around 200 to 500 B.C. and 1650 to 1750 A.D. In Iceland there was a warm period between 870 and 1264 A.D. when extensive areas were farmed that were later covered by ice. There was also a Viking expansion to Greenland centred around 1000 A.D., but the colonies became isolated and were gradually extinguished as the climate deteriorated. The colonization of Cape Hallett by penguins coincided approximately with the relatively warm period in the Norhern Hemisphere, but there is no evidence of its decline or extinction about the time of the Northern Hemisphere cold period in the seventeenth and eighteenth centuries. Presumably the temperature of the sea at Moubray Bay and in the Ross Sea did not then drop sufficiently to cause an important delay in the date of annual summer disintegration of sea-ice and so affect the penguins seriously.

Work in the Northern Hemisphere also strongly suggests that there was a long warm-dry period after the Last Glaciation, but that from 4500 B.C. onwards the climate gradually deteriorated until the time of the glacial maximum of 200 to 500 B.C. It is possible that Seabee Spit was much smaller during that warm period, if it existed at all above sea-level, but parts of the beach at the base of the cliffs might have existed, and might have been colonized by penguins. No signs were noticed of older penguin occupation but they could be hidden by younger talus and cliff-foot debris.

The possibility should not be overlooked that older penguin rookeries might be found elsewhere in the Ross Sea region, particularly at Cape Adare, and that much older Last Glaciation rookeries might be found on some of the Sub-Antarctic islands.

ACKNOWLEDGEMENTS

Thanks are extended to Mr T. A. Rafter, Director, Nuclear Science Division, D.S.I.R., for the determination of the radiocarbon age of the penguin body, and to our colleagues on the Geological Survey expedition for discussions.

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THE ANTARCTIC CONVERGENCE SOUTH OF NEW ZEALAND

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(Received for publication, 10 July 1958)

Summary

A detailed profile of temperature and salinity across the upper layers of the Antarctic Convergence worked to the north of the Ross Sea during February 1958 is discussed in terms of water movements and mixing across this major oceanic water mass boundary. The introduction of Pacific Deep Water into near surface waters is found to dominate the hydrological pattern, its influence apparently enhanced in this sector of the Southern Ocean by the position of the Pacific Antarctic Ridge in relation to deep water movements. This results in water of relatively high salinity for the Antarctic zone being found in this sector, and also introduces water of low ^{14}C activity from the very "old" Deep water into the surface pattern resulting in a significant carbon-14 depletion of Antarctic surface water.

INTRODUCTION

While in the Ross Sea sector of the Southern Ocean during February 1958 the writer made some detailed hydrological observations in the region of the Antarctic Convergence from U.S.S. *Brough (DE 148)* which was providing ocean picket support to aircraft movements between New Zealand and McMurdo Sound during *Operation Deep Freeze III* of the United States Navy. Observations were made as part of the New Zealand IGY programme.

DATA

Observations used in this discussion were made between the Antarctic Circle and latitude 60° S in approximate longitude 171° E (Fig. 1) from 5 to 8 February 1958, and consisted of the following:

(a) Continuous records of sea temperature at a depth of 3 to 5 metres (engine-room sea water injection).

(b) Bathythermograph temperature profiles to a depth of 275m at average intervals of about 10 nautical miles.

(c) Salinity profiles at similar intervals to a depth of 125m using a Spilhaus-type Sea Sampler collecting at depths of 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, and 125m.

(d) Deep serial reversing bottle stations at two points in the profile, one (A356) at the northern end to a depth of 2,000m, the

N.Z. J. Geol. Geophys. 1 : 577-94.

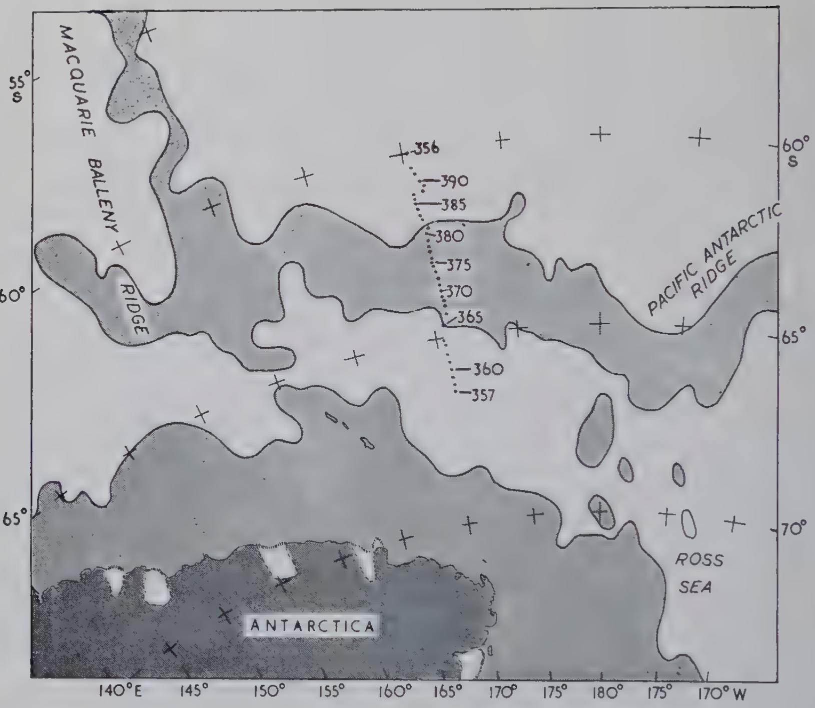

Fig. 1.—A plot of station positions occupied from U.S.S. *Brough* during February 1958. The shaded areas denote depths less than 1,500 fathoms (based on Chart H.O. 2962).

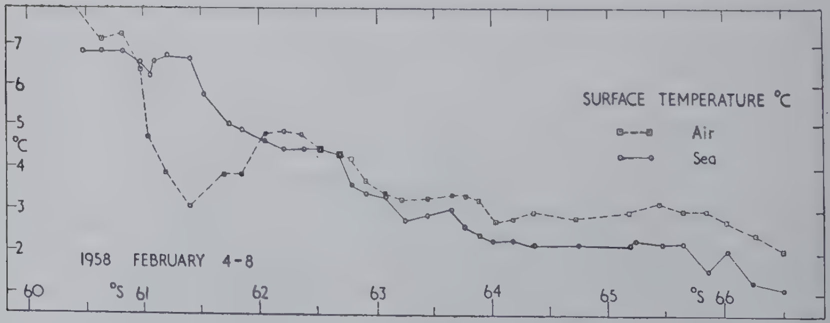

Fig. 2.—A plot of surface air and sea temperatures along a meridional section across the Antarctic Convergence in approximately 171° E.

other (A366) in latitude 64° 21′ S to a depth of 1,200m, these depths being limited in the first instance by the length of wire available and, in the second, by a rising wind and ship drift. Station A356 was worked before the section was started, on 1 February. At these stations temperature and salinity were measured at the International Standard Depths. Salinity was measured on board using a C.S.I.R.O. Portable Chlorinity Bridge (Hamon, 1956) as a transfer instrument between Copenhagen "normal water" and the unknowns.

(e) Two 40-gallon surface samples were taken at each end of the profile (at stations A356 and A357) for the determination of ^{14}C activity by the Nuclear Sciences Division, D.S.I.R., and yielded results of interest to the present discussion (Table 1).

TABLE 1.—^{14}C Activity of Surface Waters Collected from U.S.S. *Brough.*

N.Z.O.I. Station No.	*Latitude* (° S)	*Longitude* (° E)	*^{14}C depletion* (% w.r.t. contemporary *Pinus* standard)
A357	66° 29′	170° 55′	$+6{\cdot}26 \pm 0{\cdot}33$
A393	59° 56′	169° 38′	$+2{\cdot}29 \pm 0{\cdot}35$
A394	51° 31′	169° 07′	$-0{\cdot}02 \pm 0{\cdot}50$
A395	46° 13′	171° 12′	$-0{\cdot}97 \pm 0{\cdot}84$

Each sampling position was assigned a station number of the New Zealand Oceanographic Institute; numbers A356 to A392 inclusive were occupied in the profile considered here.

The observed surface air and sea temperatures at station positions along the meridional section are shown in Fig. 2, and the distributions of observed temperature and salinity and derived density (σ_t) along the section are plotted in Figs 3, 4, and 5 respectively. Fig. 6 shows the temperature-salinity correlation at selected points in the profile. The numerical station data are appended.

ANTARCTIC HYDROLOGY

The Antarctic Convergence

The salient feature of Southern Ocean hydrology is the Antarctic Convergence, usually recognized as a zone of steep meridional gradient in sea surface temperature encircling the Antarctic continent in high latitudes and which describes the boundary between the great Antarctic and Sub-antarctic surface water masses of the Southern Ocean.

Mackintosh (1946) has described the geography of this feature and its detailed surface temperature structure from many thermograph traverses across it made during the *Discovery* investigations. Deacon (1937) described the gross three-dimensional hydrological structure of the Southern Ocean and the Convergence using conventional reversing bottle techniques, while similar work by the Norwegian (*Brategg*) Antarctic Expedition (Midttun and Natvig, 1957) resulted in a detailed study of the eastern and central sectors of the Pacific Antarctic Ocean. The first detailed temperature cross-sections of the Antarctic Convergence in the Pacific Sector using the bathythermograph were contributed by United States Naval activity during Operation *Highjump* 1947 (Pritchard and LaFond, 1952) and continued during Operation *Deepfreeze,* 1955 to date (Anon., 1955, 1957a).

Water Mass Properties

Deacon (1937) defined an Antarctic circumpolar layer one to two hundred metres deep which is cooled during winter to a homogeneous surface mass with a temperature near freezing, and termed it the *Antarctic Winter Water*. In summer, through insolation and melting of ice, the upper part of this layer is warmed and has its salinity lowered to form the *Antarctic Summer Water*. These water masses are together referred to as the *Antarctic Upper Water*. The northern part of the Southern Ocean is characterized by the *Sub-antarctic Surface Water,* warmer than the Antarctic Upper Water, and with both temperature and salinity increasing progressively northwards. Under the influence of prevailing winds, the movement of Antarctic Upper Water is mainly east-going north of about 65° S and west-going farther south. Driven by meridional differences in density the Antarctic Upper Water also spreads northwards until it meets the lighter Sub-antarctic Surface Water at the Antarctic Convergence and sinks to a deeper level giving rise to the *Antarctic Intermediate Water* through mixing with the adjacent upper and deep layers. Deacon describes a *Deep Water* with origins in the Atlantic and Indian Oceans and showing a marked south-going component flowing horizontally until it reaches the Antarctic region where it rises steeply over the *Antarctic Bottom Water* derived from Antarctic shelf waters. The position of the Convergence at the surface was thus related fundamentally to the northwards spread of Bottom Water, and this in turn depends on the bottom topography and distance from its source.

DISCUSSION OF DATA

In terms of criteria for recognizing the Antarctic Convergence as a steep meridional gradient in surface temperature (Fig. 2), and as the northward limit of the subsurface temperature inversion characteristic of the Antarctic Upper Water in summer (Fig. 3), the 3° C isotherm may be used to trace the boundary between Antarctic and Sub-antarctic water, and hence the Antarctic Convergence.

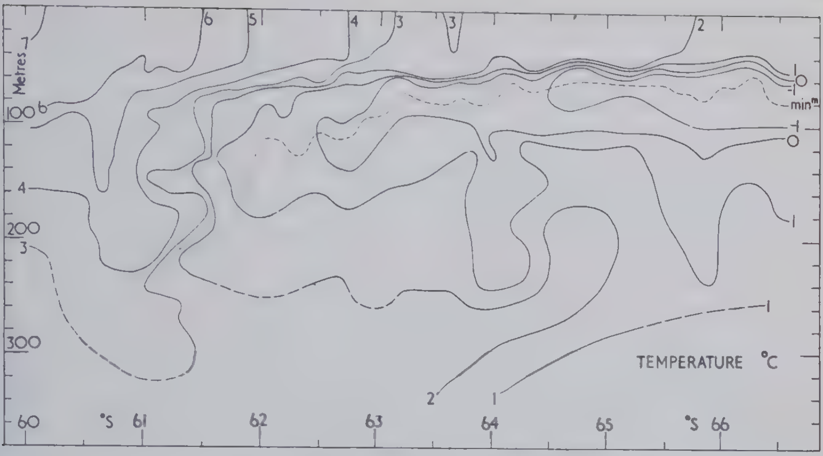

FIG. 3.—A vertical cross-section of temperature across the Antarctic Convergence in approximately 171° E.

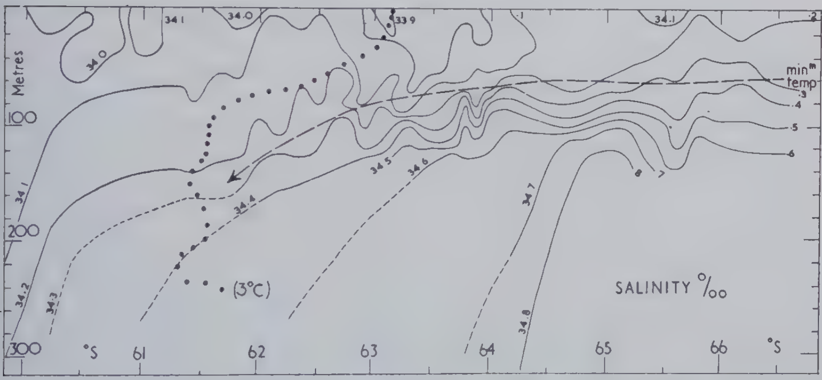

FIG. 4.—A vertical cross-section of salinity across the Antarctic Convergence in approximately 171° E.

Antarctic Summer Water occupies the almost homogeneous surface layer colder than 3° C down to the summer thermocline at a depth of some 50 metres. Immediately below this thermocline lies the cold core of the Antarctic Winter Water which sinks abruptly under the Sub-antarctic Surface Water in about south latitude 62° from a depth of some 80m to about 140m. It retains its identity nearly to 61·5° S, north of which occurs a marked change in the vertical temperature structure in upper layers of the water column. Water warmer than 3° C can be labelled as "sub-antarctic" for purposes of the present discussion, and Fig. 3 shows that this water overrides Antarctic Winter Water between about 61·5° S and 63° S, with a warm surface pocket, possibly an isolated remnant from an earlier southward movement of sub-antarctic water, which persists about 30 miles to the south of the surface outcrop of the 3° C isotherm. This last feature, together with the secondary steep meridional gradient of surface temperature apparent (Fig. 2) over the northernmost limit of Antarctic Winter Water gives the impression of an active interplay between sub-antarctic and antarctic influence, a matter discussed further in a later section.

The Salinity Pattern

Little detail is evident in the salinity structure of upper layers in the section (Fig. 4), surface salinities ranging, in general, between 33·9‰ and 34·1‰ without systematic meridional variation. Any characteristic difference in salinity between antarctic and sub-antarctic surface waters appears here to be subordinate to the effects of local environment, probably the pattern of precipitation in particular. Little ice was encountered while working the section. One moderate-sized berg was seen at the Antarctic Circle, a group of three bergy bits was passed in 65° S and the northernmost ice observed was a moderate berg in 64° 07′ S.

North of the Convergence, as marked by the 3° C isotherm, the salinity level remains fairly low and without marked variation with depth. South of the Convergence, however, a well-developed halocline appears, the top of which traces, approximately, the core of the Antarctic Winter Water. Across the Convergence region, isohalines slope steeply downwards towards the north. The vertical salinity gradient is most strongly developed around latitude 65° S where very high salinity water (> 34·7‰) appears in near-surface layers. This water seems to have the properties of Deacon's Deep Water and its presence at this depth near the southern slopes of the Pacific Antarctic Ridge suggests an interaction between this feature and water movements guiding deep water upwards into near surface layers. This observation adds confirming evidence to suggestions concerning Pacific Antarctic circulation offered by Midttun and Natvig (1957, pp. 41, 49) who extended the results of the *Brategg* observations into the Ross Sea sector of the Southern Ocean using *Discovery* material. They point out that surface isopleths (temperature, salinity, and dynamic height) seem to show a marked northwards deflection west from about 150° W and suggest the presence of a large cyclonic eddy in the general east-going movement of the Antarctic Circumpolar Current (West Wind Drift) north of the Ross Sea. They further point out (*op. cit.*, pp. 35, 36) that *Brategg* data show upper layers in the southern part of this area to be dominated by "lower deep water" (Deacon's "Warm Deep Water") while observations made farther east show much lower salinity at comparable depth. It was suggested that high surface salinities would be found outside the Ross Sea and over the southerly slope of the "South Pacific Ridge" (Pacific Antarctic Ridge) west of 140° W, due to heavy, deep water rising towards the sea surface.

The Density Pattern

The salinity pattern exerts a controlling influence on the density structure of the section (Fig. 5). The inherently unstable temperature situation in the Antarctic Upper Water is balanced by the strong increase in salinity with depth across the temperature inversion. Also, the strong downward trend of isohalines through the region of the Antarctic Convergence results in a smooth continuity of water density through the fairly abrupt temperature increase at the limit of northwards penetration of Antarctic Winter Water. Small-scale hydrostatic instabilities do appear in the density profile near positions of relatively steep density gradients, and give some idea of the scale of hydrodynamic activity present in the section associated with turbulent exchange between the various water masses involved.

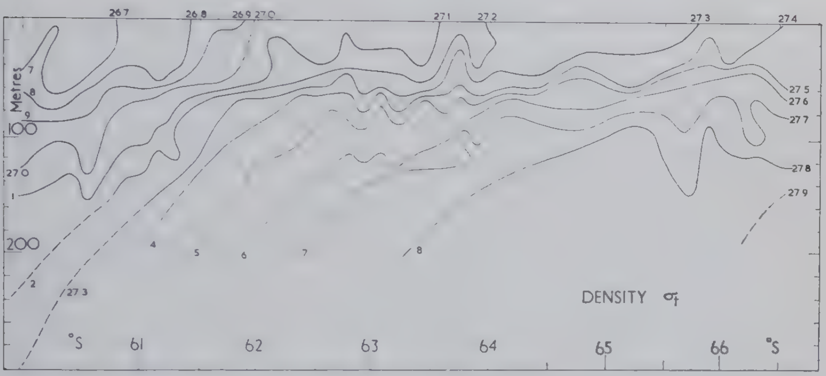

FIG. 5.—A vertical cross-section of density across the Antarctic Convergence in approximately 171° E.

While definite indication appears in the surface temperature plot of a boundary zone between sub-antarctic and antarctic waters, the dilution of surface waters results in no comparably definite discontinuity in surface water density which would mark the localized sinking of heavy antarctic surface water with a north-going component of motion. Northwards flow due to meridional thermohaline differences would probably be greatest in the layer of Antarctic Winter Water, however, and in so far as the most significant components of mixing and mass transport are likely to occur along isopycnal surfaces, the density distribution is favourable for water in the upper part of this layer to sink steeply below the Sub-antarctic Surface Water, particularly between the isopleths of σ_t 27·2 and 27·3. It may be noted that Midttun and Natvig (1957, p. 59) derive the surface source and subsequent subsurface movement of Antarctic Intermediate Water in the *Brategg* sections as characterized by the density surface σ_t 27·25.

The Antarctic Divergence

A marked drop in surface temperature was recorded just north of the Antarctic Circle associated with a deepening of the thermocline and an increase in salinity. The general slope of isopycnals, downwards to the north through the section, is consistent with the dynamics of an east-going gradient current, but this slope is reversed at the southern end of the section. While observations were not extended sufficiently far southwards to resolve the point, it may be that here is marked the boundary between the East and West Wind Drifts. This boundary has been regarded (Anon., 1957b, p. 1) as a zone of general upwelling, and called the *Antarctic Divergence*. It might be pertinent to enquire into the relation between such an upwelling movement and a preferred point where the Deep Water enters the near-surface region, with its consequent control on the position of the Antarctic Convergence to the north.

^{14}C Activity

Surface waters at each end of the section were found to be significantly depleted in ^{14}C activity with respect to the contemporary softwood *Pinus* (Table 1) used for reference. Samples taken in the sub-antarctic zone farther north were essentially of zero age with respect to the *Pinus* standard. The significance of this interesting result is difficult to evaluate with the data available and further work on the distribution of ^{14}C activity in Antarctic waters is planned. The physico-chemical influences on the ^{14}C/^{12}C ratio in ocean waters as outlined by Cooper (1956) will need to be kept in mind, an attempt made to estimate the northwards flow of ^{14}C-poor water derived from the melting of "old" ice, and the contribution of the upwards moving Deep Water calculated. This has been shown (Brodie and Burling, 1958) to be of great oceanographic "age" (around 2,500 years). The admixture of a very small volume of Deep Water with the Antarctic Upper Water through normal processes of vertical turbulence could conceivably produce an appreciable apparent "age" of surface water without the hydrological properties of the Upper Water being significantly altered from their "recent" characteristics.

T-S Relationships

There is a fundamental difficulty in using T-S curves as mixing diagrams in upper water layers, since, in the present case, mixing processes which are changing the character of the Antarctic Winter Water as it spreads northwards and sinks at the Antarctic Convergence may well be disguised by external (climatic) factors which render the temperature and salinity, to some degree, non-conservative properties. Further, with neither the magnitude of the horizontal and vertical mixing components nor the horizontal velocity separately determined it can be misleading to make quantitative deductions from a tongue-like distribution of water properties in a vertical plane.

While keeping these cautions in mind, however, it is interesting to examine the progressive meridional development of the vertical T-S relation as plotted in Fig. 6. The Deep Water would seem to be represented on the mixing diagram by a point in the vicinity of A in Fig. 6. It is apparent that the Deep Water here has a somewhat higher salinity (by about 0·5‰) than has previously been recorded. From

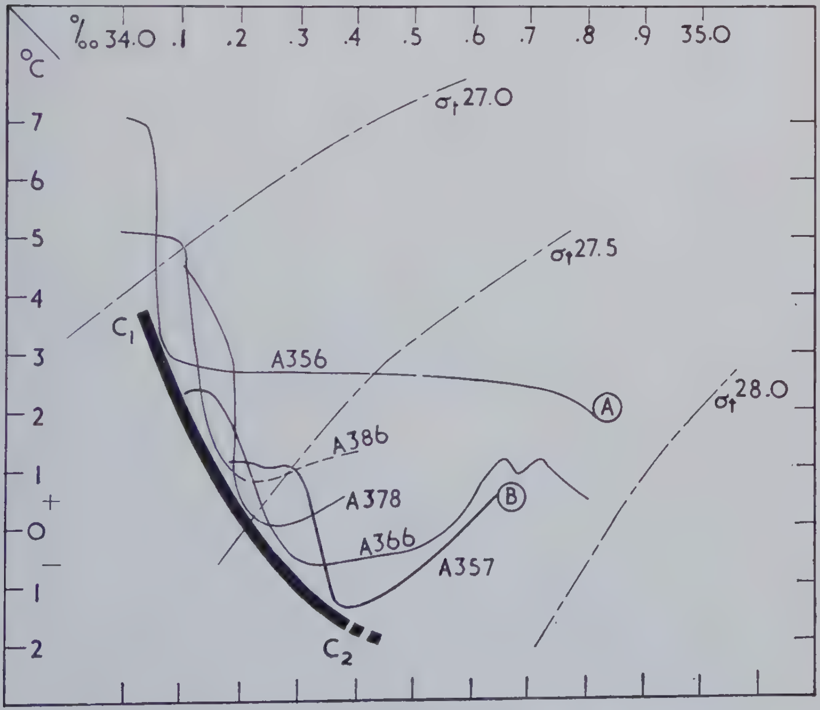

FIG. 6.—The temperature-salinity correlation at selected points in the meridional profile; stations A356, 386, 378, 366, and 357 in order of increasing latitude. Isopleths of constant potential density, σ_t, are entered for the values 27·0, 27·5, and 28·0.

recent observations made in various parts of the South-west Pacific, this effect may presently be fairly widespread and will be the subject of further study. In this *Brough* study, the two deep stations occupied (A356 and A366) did not reach a sufficient depth to enable proper definition of Deep Water characteristics, and missed the Bottom Water completely (probably characterised in Fig. 6 approximately by the point B).

The temperature minimum characteristic of the Antarctic Winter Water is very pronounced at the southern station A357. Proceeding northwards this minimum becomes less marked as the increasing surface temperature approaches that of the underlying Deep Water, until, north of the Convergence, this feature continues to be recognized as a sharp break in the T-S curve (station A356). The locus of these points (C_1C_2 in Fig. 6) is practically orthogonal to the isopleths of constant potential density, suggesting a predominance of vertical over lateral mixing to account for the progressive alteration in the character of the Antarctic Winter Water along the section. The increasing trend in salinity from north to south probably reflects the increasing influence of the rising Deep Water. The line C_1C_2 projected to meet the freezing temperature (about $-1 \cdot 9°$ C) reaches a salinity of about $34 \cdot 44‰$, which will, presumably, be close to that of the whole Antarctic Upper Water in winter. That this value is somewhat higher than average figures reported for other parts of the Antarctic region (e.g., Midtunn and Natvig, 1957, p. 73) once more suggests the effect of the Pacific Antarctic Ridge on the vertical movement of the Deep Water north of the Ross Sea From the region of the point C_1 on Fig. 6 the curve characteristic of the core of the Antarctic Intermediate Water will bend sharply to the right of the line C_2C_1, continuing practically parallel with the isopleths of constant σ_t under the influence of lateral mixing along the tongue of minimum salinity which is characteristic of this layer in more northern waters.

CONVERGENCE STRUCTURE

Midttun and Natvig (1957, p. 79), in summarising ideas on the structure of the Antarctic Convergence, state: ". . . it is clear that a southward movement (of the sub-antarctic upper layer) must take place, . . . this movement has some connection with the presence of the Antarctic Convergence." This idea perhaps neglects the possibility of convergent motion between sub-antarctic and antarctic surface waters both with a north-going velocity component derived from prevailing westerly winds, the relative convergent motion being due to an increased northwards pressure in the Antarctic water due to thermohaline effects. Any enhancement of the convergent motion due to a south-going movement in the sub-antarctic surface water would seem to require a region of upwelling somewhere in the sub-antarctic zone since a north-going component in the West Wind Drift, prevails

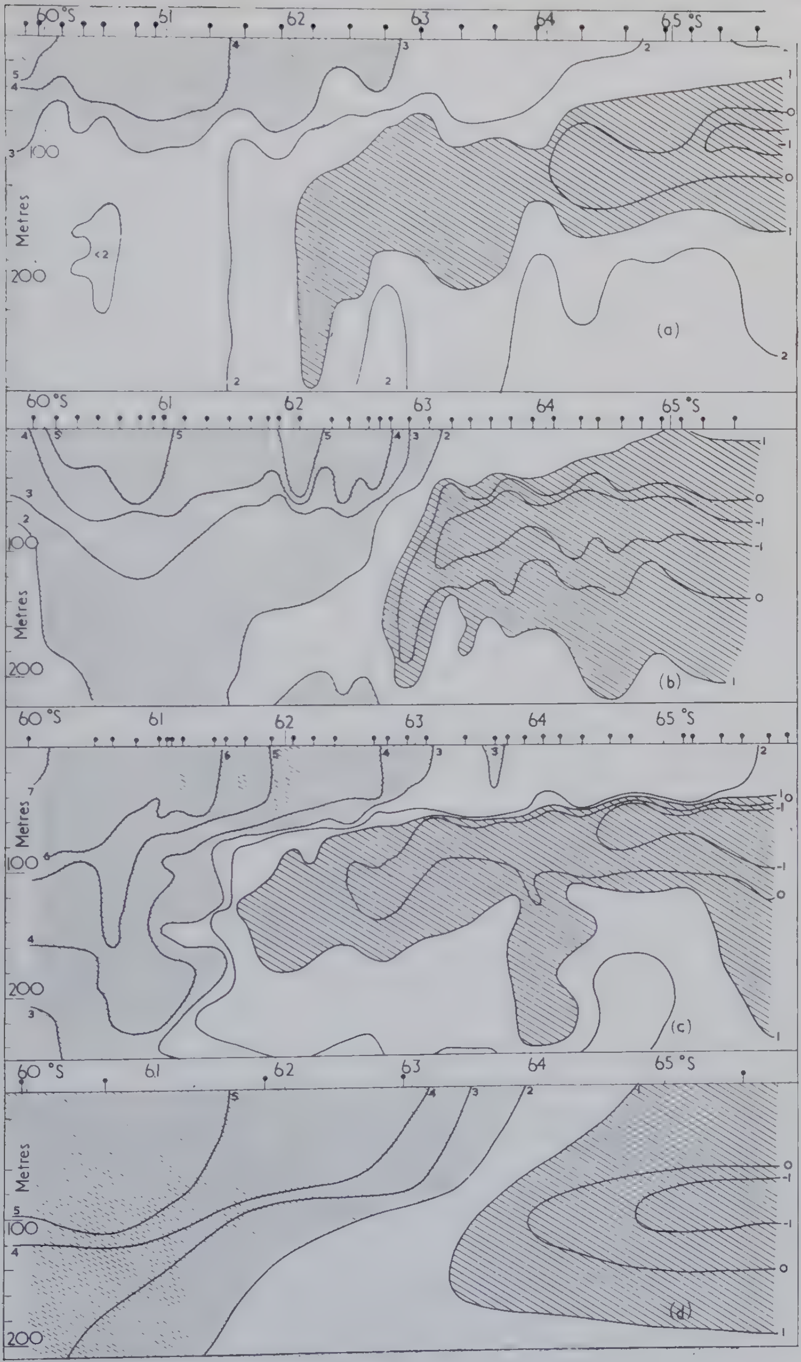

FIG. 7.—A comparison of the gross temperature structure of the Antarctic Convergence north of the Ross Sea between December 1957 and March 1958.

south of the sub-tropical convergence farther north. If the position of the Antarctic Convergence is controlled basically by deepwater movements, however, a wide range of conditions governed by local meteorological conditions could prevail in surface layers without altering the basic picture.

To give some indication of the extent of short-term variations in the structure of the Antarctic Convergence, in Fig. 7 is compared the gross temperature detail across the Convergence in the Ross Sea sector revealed by four bathythermograph sections made between December 1957 and March 1958 by: (a) H.M.N.Z.S. *Endeavour* on 24 December, in approximately 177·0° E; (b) U.S.S. *Glacier* on 2 January (records supplied by the United States Hydrographic Office) in approximately 175·0° E; (c) U.S.S. *Brough* on 7 February (data discussed previously in this paper) in approximately 171·0° E, and (d) *Endeavour* on 10 March in approximately 176·5° E.

Without simultaneous data to check on the detail of zonal variations in the structure of the Convergence, these sections will be described in terms of time variations neglecting differences in longitude. The first-mentioned possibility is of importance, however, as the development of waves and eddies in the frontal surface between antarctic and sub-antarctic water will provide significant boundary friction to major currents in these water masses, and may well exert a controlling influence on the dynamics of gradient currents in this region. Time would be well spent, therefore, in the repetition of detailed T-S sections across the Convergence, closely spaced in longitude and in time, to evaluate this effect. Each section of Fig. 7 shows the surface outcrop of the Convergence in approximately 63° S, well south of the mean position of this feature as plotted by Mackintosh (1946). Considerable variations in the development of the cold tongue of Antarctic Winter Water are apparent, however. In section (a) this tongue stops abruptly, with a "finger" pointing sharply downwards, at 62° S. For the most part, however, the core of the tongue is relatively warm, the northward limit of water less than — 1° C being well south of 65° S. Water warmer than 3° C lies north of the convergence in depths shallower than the Antarctic tongue. In section (b)—worked 9 days later, on 2 January—the sub-antarctic water has warmed and deepened slightly, while the tongue of Antarctic Winter Water has retreated to lie under the convergence at the surface in about 62° S. The cold water at the core of this tongue has intensified, however, water colder than — 1° C now extending north to the Convergence. Section (c)—worked just over one month later, on 7 February—shows this near-freezing water to have retreated southwards of 64·5° S but the Antarctic winter tongue as a whole has pushed well north (to approximately 61·5° S) under the sub-antarctic surface water. This has further warmed and deepened, the 3° C isotherm north of the tongue lying well below the level of the Winter Water. The final section (e)—worked yet another month later, 10

March—can be constructed in very general form only because of the relatively few bathythermograph soundings available. However, it is apparent that water warmer than 3° C continues to occupy a large volume north of the Convergence and that the tongue of Winter Water has retreated well to the south.

These sections give some indication of the complex interplay of factors which control the detailed structure of the Antarctic Convergence, the nature of which will make an interesting subject for further study.

ACKNOWLEDGEMENTS

The writer acknowledges with pleasure the facilities for working in Antarctic waters offered by the United States Navy; to the Hydrographic Office for the provision of special equipment, to the Commander Naval Support Forces Antarctica for facilitating arrangements for this study and to the Commanding Office and ship's company of U.S.S. *Brough* for carrying them out. Thanks are also expressed to the New Zealand Naval Board and to the Commanding Officer, H.M.N.Z.S. *Endeavour*, for measurements made from the ship.

Mr N. M. Ridgway, New Zealand Oceanographic Institute, assisted with the reduction of data

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APPENDIX

TABULAR DATA SUMMARY

STATION CIRCUMSTANCES

Station	*Date*	*Time* (N.Z.T.)	*Latitude* (° S)	*Longitude* (° E)
A356	1/2/58	0845	60° 01′	170° 22′
A357	5/2/58	1010	66° 29′	170° 55′
A358	5/2/58	1130	66° 15′	170° 55′
A359	5/2/58	1230	66° 03′	170° 55′
A360	5/2/58	1330	65° 51′	170° 54′
A361	5/2/58	1430	65° 38′	170° 48′
A362	5/2/58	1530	65° 27′	170° 45′
A363	5/2/58	1630	65° 1′3	170° 46′
A364	5/2/58	1730	65° 11′	170° 45′
A365	5/2/58	1920	64° 44′	170° 41′
A366	6/2/58	0800	64° 21′	170° 56′
A367	6/2/58	1130	64° 09′	170° 58′
A368	6/2/58	1330	64° 00′	170° 58′
A369	6/2/58	1530	63° 53′	170° 57′
A370	6/2/58	1730	63° 45′	170° 55′
A371	6/2/58	1930	63° 39′	170° 54′
A372	6/2/58	2200	63° 25′	170° 52′
A373	7/2/58	0000	63° 14′	170° 50′
A374	7/2/58	0200	63° 04′	170° 48′
A375	7/2/58	0400	62° 54′	170° 47′
A376	7/2/58	0600	62° 47′	170° 45′
A377	7/2/58	0800	62° 40′	170° 44′
A378	7/2/58	1000	62° 30′	170° 43′
A379	7/2/58	1200	62° 21′	170° 45′
A380	7/2/58	1400	62° 11′	170° 33′
A381	7/2/58	1600	62° 02′	170° 41′
A382	7/2/58	1830	61° 49′	170° 39′
A383	7/2/58	2030	61° 40′	170° 36′
A384	7/2/58	2230	61° 30′	170° 32′
A385	8/2/58	0030	61° 21′	170° 28′
A386	8/2/58	0230	61° 11′	170° 25′
A387	8/2/58	0430	61° 03′	170° 25′
A388	8/2/58	0630	61° 01′	170° 57′
A389	8/2/58	1000	60° 57′	171° 00′
A390	8/2/58	1220	60° 47′	170° 53′
A391	8/2/58	1430	60° 36′	170° 41′
A392	8/2/58	1645	60° 27	170° 33′

Station numbers refer to the registers of the New Zealand Oceanographic Institute, Wellington. Positions, especially longitudes, must be regarded as of second order accuracy only, because of continuous overcast weather throughout the work.

STATION DATA

Data for the deep stations A356 and A366 will be found at the beginning of the following tables to facilitate arrangement of material.

Depth (m)	T (° C)	S (‰)	σ_t	T (° C)	S (‰)	σ_t
		A356			A366	
0	7·05	34·00	26·68	2·33	34·11	27·27
10	7·02	·00	·68	2·31	·11	·27
20	7·01	·00	·68	2·28	·10	·26
30	7·00	·02	·69	2·25	·09	·25
50	6·96	·04	·70	2·22	·16	·30
75	6·10	·05	·82	—0·75	·31	·60
100	5·20	·06	·93	—0·15	·56	·77
150	3·66	·06	27·10	0·41	·62	·80
200	3·09	·07	·16	0·95	·69	·82
300	2·71	·20	·30	1·09	·72	·84
400	2·65	·36	·43	0·98	·72	·85
500	2·61	·46	·51	0·90	·73	·86
600	2·59	·54	·58	0·88	·74	·86
800	2·49	·64	·67	0·79	·75	·87
1000	2·34	·72	·74	0·67	·77	·91
1200	2·25	·77	·79	0·43	·80	·95
1500	2·10	·80	·83			
2000	1·82	·82	·87			
		A357			A358	
0	1·1	34·18	27·40	1·4	34·14	27·35
10	1·1	·20	·42	1·3	·17	·38
20	1·1	·22	·43	1·2	·19	·40
30	1·0	·24	·46	1·1	·22	·44
50	1·0	·28	·49	—1·2	·33	·71
75	—1·5	·37	·69	—1·5	·44	·75
100	—0·8	·50	·77	—0·9	·52	·78
120	0·1	·59	·79	0·5	·59	·82
140	0·4	·63	·89	0·8	·63	·87
		A359			A360	
0	1·6	33·81	27·32	1·7	34·20	27·38
10	1·6	34·19	·33	1·6	·22	·40
20	1·6	·21	·35	1·6	·25	·42
30	1·5	·25	·38	1·5	·28	·46
50	—1·0	·32	·62	0·0	·33	·59
75	—1·5	·42	·73	—1·5	·42	·72
100	—1·0	·52	·78	—1·0	·56	·82
120	0·1	·61	·81	—0·1	·62	·83
140	0·7	·65	·81	0·1	·67	·86
		A361			A362	
0	2·3	34·08	27·24	2·3	34·08	27·23
10	2·2	·10	·27	2·3	·10	·25
20	2·2	·19	·33	2·2	·13	·28
30	2·1	·22	·36	2·2	·18	·33
50	0·2	·28	·54	0·0	·26	·53
75	—1·5	·36	·67	—1·1	·38	·68
100	—0·7	·42	·70	—0·4	·54	·78
120	—0·4	·50	·71	0·6	·61	·78
140	0·5	·61	·78	0·7	·70	·85

Depth (m)	T (° C)	S (‰)	σ_t	T (° C)	S (‰)	σ_t
		A363			A364	
0	2·3	34·11	27·26	2·3	34·12	27·27
10	2·3	·12	·27	2·3	·12	·27
20	2·3	·14	·28	2·3	·13	·28
30	2·2	·16	·28	2·2	·15	·30
50	2·0	·20	·36	2·2	·20	·34
75	—1·0	·38	·68	—0·9	·38	·67
100	0·2	·65	·84	—0·2	·69	·88
120	1·1	·71	·83	1·1	·72	·85
140	1·2	·72	·83	1·3	·74	·85
		A365			A367	
0	2·2	34·13	27·28	2·3	34·09	27·25
10	2·2	·13	·28	2·3	·07	·22
20	2·2	·14	·29	2·2	·05	·22
30	2·1	·15	·32	2·1	·05	·23
50	—1·0	·18	·52	1·0	·10	·35
75	—1·1	·25	·57	—0·4	·40	·67
100	0·1	·50	·72	0·0	·58	·77
120	1·0	·71	·85	0·5	·62	·78
140	1·2	·72	·83	0·6	·65	·82
		A368			A369	
0	2·4	34·03	27·21	2·5	33·99	27·15
10	2·3	·01	·20	2·4	·98	·14
20	1·9	·00	·19	2·3	·99	·17
30	1·8	·02	·22	2·3	34·00	·17
50	1·0	·10	·35	2·1	·10	·28
75	—0·9	·31	·60	—0·5	·18	·50
100	—0·2	·53	·76	—0·1	·40	·70
120	0·0	·59	·78	0·4	·58	·75
140	0·3	·62	·80	0·7	·62	·78
		A370			A371	
0	2·8	33·98	27·10	3·1	33·97	27·11
10	2·8	34·10	·20	3·0	·98	·08
20	2·8	·20	·28	3·0	·99	·10
30	2·8	·29	·35	3·0	34·10	·20
50	2·2	·22	·39	2·5	·20	·30
75	—0·5	·30	·68	—0·5	·19	·55
100	—0·1	·50	·71	0·1	·30	·56
120	1·0	·52	·68	0·8	·51	·68
140	1·2	·62	·75	1·1	·61	·75
		A372			A373	
0	2·9	33·94	27·06	2·8	33·91	27·07
10	2·9	·94	·06	2·7	·91	·07
20	2·9	·95	·08	2·7	·91	·07
30	2·8	·96	·09	2·6	34·01	·16
50	2·8	·98	·11	2·1	·08	·25
75	—0·5	34·11	·47	—0·9	·05	·31
100	0·2	·29	·55	0·2	·37	·58
120	0·6	·50	·75	0·5	·41	·55
140	1·0	·61	·76	0·9	·57	·75

Depth (m)	T (° C)	S (‰)	σ_t	T (° C)	S (‰)	σ_t
		A374			A375	
0	3·2	33·88	27·00	3·4	34·00	27·08
10	3·1	·89	·02	3·3	·00	·08
20	3·0	·92	·05	3·2	·00	·09
30	2·9	34·01	·14	3·1	·04	·14
50	2·0	·08	·25	2·2	·08	·25
75	—0·6	·18	·50	0·3	·09	·37
100	—0·1	·27	·53	—0·8	·20	·53
120	0·3	·39	·61	—0·2	·30	·58
140	0·7	·51	·70	0·4	·45	·66
		A376			A377	
0	3·7	34·04	27·08	4·4	34·08	27·03
10	3·5	·04	·10	4·4	·09	·04
20	3·4	·05	·10	4·4	·10	·04
30	3·2	·08	·15	4·3	·12	·08
50	2·4	·20	·32	3·0	·20	·27
75	0·4	·18	·45	0·7	·22	·47
100	—0·1	·31	·58	0·0	·31	·57
120	—0·2	·37	·63	0·2	·32	·57
140	0·0	·43	·67	0·2	·41	·65
		A378			A379	
0	4·5	34·10	27·04	4·5	34·08	27·03
10	4·5	·11	·05	4·4	·09	·05
20	4·4	·12	·06	4·3	·10	·05
30	4·2	·13	·09	4·2	·13	·10
50	3·4	·17	·20	3·5	·18	·20
75	0·8	·19	·44	0·8	·21	·45
100	0·0	·26	·53	0·7	·25	·48
120	0·0	·29	·55	0·5	·28	·52
140	0·5	·38	·60	0·7	·38	·59
		A380			A381	
0	4·7	34·09	27·00	4·6	34·00	26·95
10	4·6	·11	·04	4·5	·00	·96
20	4·4	·12	·15	4·4	·11	27·06
30	4·3	·13	·15	4·3	·11	·07
50	4·0	·15	·14	4·1	·12	·07
75	1·7	·17	·35	1·4	·16	·36
100	0·9	·19	·43	0·9	·21	·44
120	0·7	·28	·50	0·8	·28	·50
140	0·8	·34	·56	0·9	·33	·54
		A382			A383	
0	5·0	33·98	26·89	5·1	33·99	26·88
10	5·0	·98	·89	5·1	34·00	·89
20	5·0	34·00	·90	5·1	·02	·91
30	5·0	·05	·94	5·1	·06	·94
50	4·6	·09	27·01	5·0	·09	·98
75	1·9	·14	·31	2·5	·13	27·25
100	1·1	·18	·40	1·4	·16	·36
120	1·0	·19	·42	0·9	·18	·42
140	1·0	·26	·47	0·9	·23	·45

Depth (m)	T (° C)	S (‰)	σ_t	T (° C)	S (‰)	σ_t
		A384			A385	
0	5·8	34·03	26·83	6·7	34·05	26·73
10	5·8	·03	·83	6·7	·05	·73
20	5·8	·04	·84	6·7	·05	·73
30	5·8	·05	·85	6·7	·05	·73
50	5·2	·08	·94	6·0	·08	·85
75	2·9	·10	27·20	3·5	·10	27·15
100	2·0	·14	·31	3·2	·15	·21
120	2·0	·17	·33	3·2	·17	·23
140	1·6	·20	·40	2·0	·20	·35
		A386			A387	
0	6·7	34·00	26·69	6·5	33·99	26·71
10	6·7	·00	·69	6·5	·99	·71
20	6·7	·00	·69	6·5	·99	·71
30	6·7	·00	·69	6·5	34·00	·72
50	6·5	·04	·75	6·0	·06	·83
75	4·6	·11	27·04	4·8	·11	27·02
100	3·7	·15	·16	4·0	·14	·13
120	3·4	·17	·21	3·7	·16	·17
140	3·1	·20	·26	3·5	·19	·22
		A388			A389	
0	6·5	33·99	26·71	6·5	33·99	26·71
10	6·5	·99	·71	6·5	·99	·71
20	6·5	·99	·71	6·5	·99	·71
30	6·5	34·00	·72	6·5	34·00	·72
50	6·1	·07	·83	6·0	·08	·85
75	4·8	·11	27·00	4·9	·11	27·00
100	4·0	·14	·07	4·5	·14	·07
120	3·9	·16	·13	4·1	·16	·13
140	3·3	·19	·22	3·4	·19	·22
		A390			A391	
0	6·8	34·00	26·68	6·8	33·99	26·67
10	6·8	33·99	·67	6·8	·99	·67
20	6·8	·98	·66	6·8	·98	·66
30	6·8	·99	·67	6·8	·98	·66
50	6·1	34·04	·80	6·6	·99	70
75	5·5	·10	·97	5·9	34·08	·86
100	5·0	·13	27·01	5·6	·12	·93
120	4·9	·16	·04	5·4	·15	·98
140	4·5	·18	·10	5·2	·17	27·02
		A392				
0	6·8	34·01	26·69			
10	6·8	33·99	·67			
20	6·8	34·00	·68			
30	6·8	33·99	·67			
50	6·7	·99	·68			
75	6·3	34·07	·80			
100	4·9	·12	27·01			
120	4·6	·14	·06			
140	4·3	·17	·12			